# *Climate variability and human impact in South America during the last 2000 years: synthesis and perspectives from pollen records*

Article

Published Version



Flantua, S. G. A., Hooghiemstra, H., Vuille, M., Behling, H., Carson, J. F., Gosling, W. D., Hoyos, I., Ledru, M. P., Montoya, E., Mayle, F. ORCID: https://orcid.org/0000-0001-9208-0519, Maldonado, A., Rull, V., Tonello, M. S., Whitney, B. S. and González-Arango, C. (2016) Climate variability and human impact in South America during the last 2000 years: synthesis and perspectives from pollen records. Climate of the Past, 12 (2). pp. 483-523. ISSN 1814-9332 doi: 10.5194/cp-12-483-2016 Available at https://centaur.reading.ac.uk/41205/


Published version at: http://www.clim-past.net/12/483/2016
To link to this article DOI: http://dx.doi.org/10.5194/cp-12-483-2016

Publisher: Copernicus Publications on behalf of the European Geosciences Union

Clim. Past Discuss., 11, 3475–3565, 2015
www.clim-past-discuss.net/11/3475/2015/
doi:10.5194/cpd-11-3475-2015


Climate of the Past
Discussions
Open Access



# Climate variability and human impact on the environment in South America during the last 2000 years: synthesis and perspectives

**S. G. A. Flantua[1], H. Hooghiemstra[1], M. Vuille[2], H. Behling[3], J. F. Carson[4], W. D. Gosling[1,5], I. Hoyos[6], M. P. Ledru[7], E. Montoya[5], F. Mayle[8], A. Maldonado[9], V. Rull[10], M. S. Tonello[11], B. S. Whitney[12], and C. González-Arango[13]**

[1]Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands
[2]Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY, USA
[3]Georg-August-University of Göttingen, Albrecht-von-Haller-Institute for Plant Sciences, Department of Palynology and Climate Dynamics, Untere Karspüle 2, 37073, Göttingen, Germany
[4]Department of Geography and Environmental Science, University of Reading, Reading, RG6 6AB, UK
[5]Department of Environment, Earth & Ecosystems, The Open University, Walton Hall, Miltion Keynes, MK7 6AA, UK

[6]Faculty of Engineering, GAIA, Institute of Physics Group Fundamentos y Enseñanza de la Física y los Sistemas Dinámicos, Universidad de Antioquia, Medellin, Colombia
[7]Institut des Sciences de l'Evolution de Montpellier (ISEM) (UM2 CNRS IRD EPHE) Place Eugène Bataillon cc 061, 34095 Montpellier CEDEX, France
[8]Department of Geography and Environmental Science, University of Reading, Reading, RG6 6AB, UK
[9]Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Universidad de La Serena, Av Raúl Bitrán 1305, La Serena, Chile
[10]Institute of Earth Sciences "Jaume Almera" (ICTJA-CSIC), C. Lluís Solé Sabarís s/n, 08028 Barcelona, Spain
[11]Instituto de Investigaciones Marinas y Costeras CONICET, Universidad Nacional de Mar del Plata, Mar del Plata, Argentina
[12]Department of Geography, Ellison Place, Northumbria University, Newcastle-Upon-Tyne, NE1 8ST, UK
[13]Departamento de Ciencias Biológicas, Universidad los Andes, A.A. 4976 Bogotá, Colombia

Received: 31 May 2015 – Accepted: 1 June 2015 – Published: 29 July 2015

Correspondence to: S. G. A. Flantua (s.g.a.flantua@uva.nl)
and H. Hooghiemstra (h.hooghiemstra@uva.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

An improved understanding of present-day climate variability and change relies on high-quality data sets from the past two millennia. Global efforts to reconstruct regional climate modes are in the process of validating and integrating paleo-proxies. For South America, however, the full potential of vegetation records for evaluating and improving climate models has hitherto not been sufficiently acknowledged due to its unknown spatial and temporal coverage. This paper therefore serves as a guide to high-quality pollen records that capture environmental variability during the last two millennia. We identify the pollen records with the required temporal characteristics for PAGES-2 ka climate modelling and we discuss their sensitivity to the spatial signature of climate modes throughout the continent. Diverse patterns of vegetation response to climate change are observed, with more similar patterns of change in the lowlands and varying intensity and direction of responses in the highlands. Pollen records display local scale responses to climate modes, thus it is necessary to understand how vegetation-climate interactions might diverge under variable settings. Additionally, pollen is an excellent indicator of human impact through time. Evidence for human land use in pollen records is useful for archaeological hypothesis testing and important in distinguishing natural from anthropogenically driven vegetation change. We stress the need for the palynological community to be more familiar with climate variability patterns to correctly attribute the potential causes of observed vegetation dynamics. The LOTRED-SA-2 k initiative provides the ideal framework for the integration of the various paleoclimatic sub-disciplines and paleo-science, thereby jumpstarting and fostering multi-disciplinary research into environmental change on centennial and millennial time scales.

## 1 Introduction

Accurately simulating the complexity of Earth's climate system is still a major challenge for even the most advanced earth system models. One major obstacle for evaluating





CPD
11, 3475–3565, 2015

model performance in historical runs is the lack of long and reliable climate records from regions of the world with poor data coverage. Given the scarcity of instrumental records in many regions, alternative, proxy-based climate reconstructions therefore provide an excellent dataset against which to test models and their ability to accurately simulate longer-term features of climate change. Stratigraphic records (in particular pollen, charcoal and tephra from lake sediments and peat bogs) have been particularly underutilized in this regard.

Increasingly studies have demonstrated the integration of multiple proxies (Li et al., 2010) in a climate reconstruction, with a special focus on the two millennia (2 k) before present (BP, present defined as AD 1950). This period could be considered a baseline to current conditions as climate has been very similar to the present. This integration is still in its infancy in South America (SA), especially in the tropics. Since 2009, regional climate reconstructions from this region have gained momentum by compiling multiple datasets and fine-tuning reconstruction methods (Villalba et al., 2009). An adequate spatial distribution of proxy data sets is one of the key necessities identified (Villalba et al., 2009; Flantua et al., 2015a). Fortunately, tree rings studies have expanded their geographical coverage. These constitute a widely distributed and frequently used high-resolution climate archive (Boninsegna et al., 2009; Villalba et al., 2009). However, the temporal range of tree rings records is limited compared to the expanse of spatial and temporal coverage provided by pollen records. The newly updated inventory of palynological research in SA (Flantua et al., 2015a) documents the extensive spatial and temporal coverage of pollen-based research available throughout the continent. Additionally, developing alternative recalibrated age models and evaluation of chronologies is another step forward in multi-proxy integration in SA (Flantua et al., 2015b). However, multi-proxy climate reconstructions from the last 2 ka have hitherto been focused mainly on southern SA (PAGES-2 k Consortium, 2013), omitting input from the northern two thirds of the continent. Furthermore, palynological research has been underrepresented in most reconstructions of climate variability (Villalba et al., 2009; Neukom et al., 2010; Neukom and Gergis, 2012). The lack of an adequate overview of available pollen





CPD
11, 3475–3565, 2015

records from the continent has been an impediment to the advancement of its use and inclusion in climate studies.

As a result, we identified the need to review and discuss pollen records in SA that can fulfil requirements for inclusion in 2 ka-paleoclimate reconstructions, within the framework of LOng-Term multi-proxy climate REconstructions and Dynamics in South America (LOTRED-SA, this Special Issue) and PAGES-2 k. This paper is structured following an assessment for individual regions in SA within the context of current climate modes. These modes are characterized by their precipitation and temperature fingerprint over South America and used as a baseline framework to identify past climatic changes from pollen records. Certain zones are more prone to particular climate signals, therefore comparison between the spatial expression of climate modes and highly correlated records from different regions strengthens the interpretation of paleoecological findings. To use pollen as a palaeoclimate proxy, the degree of human impact on the vegetation needs to be considered minimum or absent over the last 2 ka. Therefore, drivers of vegetation change, both natural and anthropogenic, are discussed within the different regions to describe the general settings required for paleoecological research in the last millennia. Records that identify significant human impact are identified and excluded from the proposed dataset for PAGES-2 k, but are considered useful within the regional purposes of LOTRED-SA (this Special Issue). We finish by discussing the potential of including pollen-inferred climate information 2 ka-climate model validation and emphasize the importance of multi-proxy working groups such as LOTRED-SA.

## 2 Climate settings

We begin with an overview of the main climate "zones" of South America to provide the climatological context for a discussion of pollen records covering the past 2000 calibrated years before present (cal kyr BP; in this paper abbreviated to "ka"). Climate zones are regions of coherent seasonality and mean climate (intra-annual climate regime), while climate "modes" (discussed below) are based on ocean–atmosphere





CPD
11, 3475–3565, 2015

interactions with often oscillatory behaviour affecting the interannual to multidecadal climate variability in a region. Most palynological studies merely describe climate zones for their discussion of vegetation response to climate. However, interannual to multidecadal variability is equally relevant for the interpretation of spatial variability detected by pollen records. Therefore in this paper we provide a detailed exploration of the influence of these modes on South American climate. The spatial influence of climate modes is assessed by documenting their role in driving interannual precipitation and temperature variability. Following this climatic framework, we explain the procedure for selecting robust pollen records in seven regions and assess the regional significance of climatic and human drivers of vegetation change over the last 2 ka. Records along coastlines influenced by sea level changes were not included.

### 2.1 Continental overview climate zones and modes

Continental SA extends from the tropics (12° N) to mid-latitudes (55° S). Three major noticeable climate zones can be distinguished; tropical South America, subtropical South America and austral South America. Atmospheric circulation and climate in all three zones is highly modulated and constrained by the orography of the Andes, the shape of the continent and interactions with the underlying land-surface, vegetation and soil moisture (Wang and Fu, 2002; Li and Fu, 2006).

The climate of tropical SA is dominated by the seasonal migration of the Intertropical Convergence Zone (ITCZ) over the Atlantic and Pacific, and the seasonal development of convective activity associated with the South American Summer Monsoon (SASM) over the interior of the continent (Fig. 1). The seasonal migration of the ITCZ affects primarily coastal areas and northernmost SA as it is characterized by a fairly well constrained narrow band of low level wind convergence over the equatorial oceans. The SASM is a seasonal phenomenon that develops between September and April and affects primarily the Southern Hemisphere tropics and subtropics (Garreaud et al., 2009). During the austral spring–summer (December to February, DJF) transition, moisture influx from the ITCZ contributes to the development of this monsoon system (Zhou





CPD
11, 3475–3565, 2015

and Lau, 2001; Vuille et al., 2012). This monsoonal system reaches its mature phase (maximum development) during DJF and is characterized by heavy rainfall advancing southward from tropical to subtropical latitudes. To the east of the tropical Andes a strong low-level wind, the Andean low-level jet (ALLJ), transports moisture in a northwest (NW) to southeast (SE) direction from the tropics to the subtropical plains (Cheng et al., 2013), feeding the South Atlantic Convergence Zone (SACZ), extending from the SE Amazon Basin toward the SE out over the S Atlantic. The austral region is characterized by a quasi-permanent westerly circulation embedded in-between the subtropical anticyclones located over the subtropical Pacific and Atlantic to the N and the austral polar low to the S. Frequent northward propagation of extratropical cold air incursions east of the Andes provide for continued atmospheric interaction and heat exchange between mid- and low latitudes over the subtropical continent. The latitudinal extension of the westerlies over land displays limited variations across the year and covers southern and central (C) Argentina and Chile (Fig. 1). Additional information is presented in the Supplement.

Both precipitation and temperature exhibit significant variability on interannual to interdecadal time scales in all three climate zones of SA (e.g. Garreaud et al., 2009). This variability is mainly caused by ocean–atmosphere interactions (Vuille and Garreaud, 2012) that lead to a reorganization of the large-scale circulation over SA and the neighbouring oceans. To quantify the influence and relative importance of these ocean–atmosphere coupled modes on the interannual precipitation and temperature variability over SA, spatial correlation and regression coefficients are calculated.

Gridded precipitation and temperature data were derived from the UDelaware data set V2.01 (Legates and Willmott, 1990) at 0.5° resolution. We limit our assessment to the six most relevant climate modes (Table 1). Other modes analyzed were either largely redundant or showed a much weaker influence over the SA continent. The resulting correlation maps indicate the correlation coefficient on interannual time scales between the mode in question and the local temperature and precipitation at each grid cell. Conversely, the regression maps indicate the local anomaly (in physical units of





CPD
11, 3475–3565, 2015

mm or °C) at each location that corresponds to a unit (one standard deviation) anomaly in the climate mode. The Southern Annular Mode (SAM) and all three Atlantic modes (Atlantic Multidecadal Oscillation, Tropical North and South Atlantic Sea Surface Temperature, Table 1) were detrended prior to analysis to ensure that correlation and regression coefficients account for co-variability on interannual timescales only and do not result from spurious common trends. More information on the methodology can be found in the Supplement.

In all correlation maps (Figs. 2 and 4) we show correlations in excess of ±0.2 only, which approximately corresponds to the 95 % significance level. For the regression maps (Figs. 3 and 5) we used thresholds of ±0.12 °C and ±50 mm, respectively. The correlation maps can help inform whether a certain temperature or precipitation anomaly in the regression map is statistically significant. In our discussion we focus primarily on the impact of the positive phase from each of these modes, as these are the fingerprints presented in Figs. 2–5. Since this is a linear analysis the negative phase of these modes would lead to the same changes in temperature and precipitation, but with the sign reversed. In general these outcomes are consistent with earlier analyses reported by Garreaud et al. (2009). However, some differences are apparent and most likely related to different time periods analyzed, our choice of using the hydrologic year as opposed to the calendar year, and different definitions of the indices used (see Supplement for more details). For example, Garreaud et al. (2009) used the Multivariate El Niño Southern Oscillation (ENSO) Index, while here we focus on the Niño3.4 index to describe ENSO variability. Similarly Garreaud et al. (2009) used the Pacific Decadal Oscillation Index to describe Pacific interdecadal variability, while here we use the Interdecadal Pacific Oscillation (IPO).

## 2.2 Temperature

The largest and most significant influence on temperature variability in SA is exerted by ENSO, with above average temperatures during El Niño and reduced temperature during La Niña (Figs. 2 and 3). Temperature variations in western SA, and particularly



CPD
11, 3475–3565, 2015

along the Pacific coast, can reach > 0.8 °C which is associated with a one standard deviation departure in the Niño3.4 index. In the Andes of Colombia the correlation between temperature and the Niño3.4 index is > 0.8, indicating that more than two thirds of the temperature variability on interannual time scales can be explained by ENSO. The largest increase in temperature is observed during austral summer (DJF, not shown) linked to the peak phase of ENSO, which tends to occur at the end of the calendar year.

The IPO has a similar, albeit slightly weaker, fingerprint over SA as ENSO, which is not surprising given that Pacific decadal and multidecadal variability is often described as "ENSO-like" (e.g. Garreaud and Battisti, 1999). Its impact extends further south along the west (W) coast of SA, however, with a somewhat stronger influence on temperature in N-C Chile. It is noteworthy that the IPO impact over SA is almost identical to the influence of the Pacific Decadal Oscillation as described in Garreaud et al. (2009).

The N Atlantic modes, Atlantic Multidecadal Oscillation (AMO) and Tropical North Atlantic SST (TNA) are also quite similar, both featuring warming over tropical SA during periods when sea surface temperature (SST) in the N Atlantic domain are above average, most notably so over the southern C Amazon Basin (Figs. 2 and 3). In fact the warming associated with a unit variation in the AMO or TNA index is larger over most of the Amazon Basin than the warming associated with ENSO. The region of largest warming is co-located with an area of strong precipitation reduction during the warm phase of the TNA and the AMO (Figs. 4 and 5). This suggests that much of the warming is caused by cloud cover and soil moisture feedbacks associated with reductions in precipitation (reduced cloud cover leading to enhanced solar radiation and reduced soil moisture limiting evaporative cooling).

The S Atlantic counterpart, the TSA, is associated with a temperature dipole over subtropical SA, characterized by warming along a zonal band extending from the S-C Brazilian coast westward to Bolivia, while C Argentina contemporaneously experiences cooling (Figs. 2 and 3). The warming in the subtropical region coincides with a region of reduced precipitation during the TSA positive phase (Fig. 4), suggesting that the





CPD
11, 3475–3565, 2015

warming is at least in part caused by changes in the hydrologic cycle (cloud cover and/or soil moisture feedbacks).

The SAM is positively correlated with temperature over Patagonia (Fig. 2) and also shows a weak negative temperature departure over western tropical SA during its positive phase (Fig. 3). The warming over Patagonia is strongest during austral summer (Garreaud et al., 2009; not shown) and results from enhanced heat advection, combined with higher solar radiation receipts due to cloud free conditions (Gupta and England, 2006).

### 2.3 Precipitation

Given that ENSO is the source of the strongest interannual variability on Earth, it is not surprising that it also leads to the strongest modern precipitation anomalies over SA (Fig. 5). In general in the tropics, El Niño events lead to significant precipitation reductions over much of tropical SA, with the strongest signal seen in N Brazil along the Atlantic coast and in the Andes of Colombia. Over NE Brazil the precipitation reduction is the result of El Niño events inducing a delayed anomalous warming of the tropical N Atlantic in boreal spring (e.g. Curtis and Hastenrath, 1995; Giannini et al., 2001). Hence the ENSO influence in this region strongly projects onto the TNA pattern (Fig. 4). Over the N Amazon Basin the precipitation reduction is the result of a shifted Walker circulation, enhanced subsidence and reduced convective activity (e.g. Liebmann and Marengo, 2001; Ronchail et al., 2002). In the subtropics on the other hand precipitation is enhanced during El Niño events, in particular over southeastern SA (see also Grimm et al., 2000). The only tropical location that sees an increase in precipitation during El Niño is along the Pacific coast of Ecuador and northern Peru, where flooding is a common occurrence during these events (e.g. Takahashi, 2004). During La Niña events these precipitation anomalies are essentially reversed. The correlations are weaker in our annual analysis over some regions where the ENSO influence is highly seasonal, such as the precipitation reduction over the “Altiplano” (high plain)





CPD
11, 3475–3565, 2015

region in DJF (Vuille et al., 2000) or the enhanced precipitation during El Niño in C Chile in June to August (JJA; Montecinos and Aceituno, 2003).

The largest change in the IPO in the period analyzed is related to the Pacific climate shift of 1976–1977, when the tropical Pacific switched from its cold to its warm phase. Since El Niño events also became more frequent and stronger over this period (including the two extreme events of 1982–1983 and 1997–1998), it is no surprise that the observed changes in precipitation associated with the IPO are similar to the ENSO footprint, albeit somewhat weaker. Indeed the low-frequency modulation by the IPO may strengthen El Niño events during its positive phase and weaken La Niña events, while the opposite is the case during the IPO negative phase, a phenomenon known as "constructive interference" (e.g. Andreoli and Kayano, 2005). Espinoza Villar et al. (2009) documented the influence of Pacific interdecadal variability on precipitation over the Amazon Basin and showed that its positive phase is related to a decrease in precipitation over the basin since 1975, consistent with our results.

Precipitation is reduced in the southernmost part of SA during the positive phase of the SAM (Fig. 4). This reduction extends N into the subtropics along both the Atlantic and Pacific coast to approximately 30° S (Silvestri and Vera, 2003; Gillett et al., 2006). Most of this precipitation reduction is associated with reduced westerly moisture flux and moisture convergence from the Pacific (Garreaud et al., 2013). The correlation (Fig. 4) and regression (Fig. 5) maps also suggest a significant influence of the SAM on precipitation in parts of the tropics. This signal, however, is not well documented and its physical mechanism is unclear. It may to some extent be related to teleconnections and an anticorrelation between ENSO and the SAM (e.g. Carvalho et al., 2005), which is supported by the fact that the Niño3.4 index and the SAM correlation maps are almost mirror images of one another (Fig. 4).

The AMO and the TNA have a similar fingerprint on the hydrologic cycle of SA (Fig. 5). Both modes are characterized by a significant reduction in precipitation over much of the Amazon Basin during their positive phase, with the amplitude of the changes being slightly larger associated with TNA forcing. This negative precipitation





CPD
11, 3475–3565, 2015

anomaly is associated with the northward displacement of convective activity in the ITCZ region due to warmer SST in the tropical North Atlantic and Caribbean during the positive phase of the TNA (and to a lesser extent also the AMO). This directly affects precipitation amounts over NE Brazil (e.g. Hastenrath and Greischar, 1993; Nobre and Shukla, 1996), while the northward shift in the core region of convection also leads to anomalous subsidence, located over the Amazon basin. In fact the recent droughts in 2005 and 2010 in the Amazon Basin were both associated with such anomalously warm SST in the tropical N Atlantic (Marengo et al., 2008; Lewis et al., 2011). The only region where precipitation is enhanced is in the NW part of the Amazon belonging to Venezuela, Colombia and Peru (Fig. 4).

An anomalously warm tropical S Atlantic (positive phase of the TSA) leads to the exact opposite conditions, with the ITCZ displaced anomalously far south, causing copious rainfall over NE Brazil, with weaker positive anomalies extending inland as far as the Peruvian border (Fig. 5). Another region of enhanced precipitation is located in S Brazil, associated with a southerly movement of the SACZ (Fig. 1; e.g. Doyle and Barros, 2002).

## 3 LAPD overview and selection of pollen records covering 2 ka

From the newly updated Latin American Pollen Database (LAPD, Flantua et al., 2015a) we selected the records that cover the last 2 ka. Good chronological control is required for PAGES-2 k, but the youngest ages in pollen records are typically constrained by geochronological data. An assessment of the pollen records by the authors with expertise in each sub-region of SA has revealed 585 records with pollen samples within the 2 ka-range (Fig. 6), of which 337 and 182 records, respectively, contain one or more geochronological date within that time period. Thus, 182 studies were considered suitable for paleoclimate reconstruction as outlined by the PAGES-2 k criteria.

Within the working groups of PAGES, the "2 k-Network" was initially established in 2008 to improve current understanding of temperature variability during the last 2 ka.





CPD
11, 3475–3565, 2015

Through the identification of temperature sensitive proxies, the development of climate reconstructions has advanced thanks to regional efforts (e.g. LOTRED-SA) to compile a proxy database (PAGES-2 k Consortium, 2013). Both temperature and moisture records are currently being collected, requiring a set of criteria that define the suitability of individual records.

As a global initiative, a defined set of criteria guarantees the quality of the proxies used for climate reconstructions and therefore focuses on chronological accuracy and record resolution (Table 2). Within this paper we regarded criteria A (peer-reviewed publication) and B (minimum duration of the record of 500 years) as the base line criteria. All criteria followed those stated by PAGES-2 k except for the criterion on resolution. Implementing the criteria of a maximum resolution of 50 yr $sample^{-1}$, would leave only a handful of pollen records to discuss. The sparsity of samples that meet the stringent PAGES-2 k resolution criterion occurs because palaeorecords with long time spans (> 10 000 years) are typically sampled at coarser temporal resolution. Furthermore, many lowland sites have very low sedimentation rates, which preclude high-resolution sampling. Therefore we propose a more flexible temporal resolution, depending on the identified relevance of the case study. Records with a resolution of 200 to 300 years are included in our discussion. Within the regional assessments, only records that fulfil more than three criteria are discussed, unless the records are considered particularly valuable for regional climate assessments.

## 4 Results

### Regional assessments

Pollen records are discussed according to their regional and geographical settings (Fig. 6a–g). The references to all records discussed are presented in Table 3. The maps of Figs. 6–14 were created using ArcGIS 10.1™ software (Esri, 2012).





CPD
11, 3475–3565, 2015

## 4.1 Climate–vegetation interaction in the Venezuelan Guayana highlands and uplands

The study area, known as the Gran Sabana (GS), is located in SE Venezuela between the Orinoco and Amazon basins (Fig. 6a; Huber and Febres, 2000). Huber (1995) recognized three main elevational levels on the Venezuelan Guayana: lowlands (0–500 m a.s.l.), uplands (500–1500 m a.s.l.) and highlands (1500–3000 m a.s.l.). Lowlands are absent in the GS, which is mainly characterized by a continuous upland peneplain spiked with isolated highlands (table-mountains, "tepuis"). The GS highlands are part of the so-called Pantepui phytogeographical province, which is characterized by unique biodiversity and endemism patterns, encompassing all the tepui summits above 1500 m a.s.l. (Huber, 1994; Berry et al., 1995). The tepuian vegetation is characterized by a mosaic of bare rock, pioneer vegetation, tepuian forests, herbaceous formations and shrublands (Huber, 1995b). Additional background information is provided in the Supplement.

In the GS, 22 pollen records cover the last 2 ka. There are 4 records with a chronology based on one control point and an additional 10 records from which most, or all, control points lie outside 2 ka. Three potentially suitable records originate from the highlands, `Eruoda PATAM6-A07`, `Churí Chim-2` and `Apakará PATAM9-A07`, and only 1 is found in the uplands, `Laguna Encantada PATAM4-D07` peatland (Fig. 7a; Table 3). Of the 3 records of the highlands, just `Eruoda` provides sufficiently high resolution to explore the objectives proposed here. However, only `Churi Chim-2` and `Apakará` contains several age control points within the last 2 ka, and `Laguna Encantada` presents a relatively low sampling resolution of 200 to 300 years.

The criteria for chronological control has excluded some of the most relevant work for the research questions posed by this paper. For example, the vegetation at the `Eruoda` summit has persisted unchanged during the last ~ 2.5 ka. This constancy can be extended to all the tepuian summits studied so far during the last 6 ka (except `Churí`). Based on the absence of human activities in these summits, it can be assumed that





CPD
11, 3475–3565, 2015

the vegetation dynamics observed in the fossil records are fully climate driven and therefore a record valuable for LOTRED-SA. Equally of high importance is the Urué record in the uplands, which does not meet the dating control constraints but the sampling resolution is high enough to provide important insights into the vegetation-climate dynamics during the last 2 ka, and will be therefore be presented here.

The Eruoda summit represents an important reference to which almost all the tepuian summits vegetation dynamics can be compared (Fig. 7b). In general, these summits are insensitive to temperature change (for 2 ka), whereas moisture variations potentially may cause small internal reorganisations of plant associations although these shifts are considered to be of minor ecological significance. Shifting river courses are considered to influence local vegetation patterns through the lateral movement of gallery forests in landscapes dominated by broad-leaved meadows (Rull, 2005a, b).

The Urué sequence spans the last 1.6 ka and records the vegetation dynamics after an important fire event dated ∼ 1.6–1.8 ka. Three main vegetation stages were reported coeval with high charcoal abundances at the bottom of the sequence, corresponding to plant communities' transitions from open secondary forest to fern-dominated associations transitional to savanna. Savannas were fully established around 0.9 ka, coinciding with the beginning of a phase of lower charcoal values, and continued as the dominant plant association until present-day. Savannas were accompanied by *Mauritia flexuosa* palm swamps ("morichales") that established a phase that was likely more humid. These palm swamps greatly varied in extent through time, showing a parallel between the lowest palm abundance and two drought intervals' occurrence. These two drought intervals were centred during the 0.65–0.55 and 0.15–0.5 ka coeval to the Little Ice Age (LIA) signal observed in the Venezuelan Andes (Rull et al., 1987; Rull and Schubert, 1989; Polissar et al., 2006). Generally, the vegetation dynamics recorded so far in the Venezuelan Guayana uplands have shown a higher sensitivity to changes in the available moisture than to potential shifts in the average temperatures. The last 2 ka have been mainly characterised by vegetation change at a local scale.





CPD
11, 3475–3565, 2015

## 4.2 Climate–vegetation interaction in the Northern Andes

The region of the N Andes consists in political terms of Colombia, Ecuador and Venezuela and includes a wide range of different ecoregions (Fig. 6b). Sharing both the Caribbean and the Pacific coastline and various climate influences, Colombia has a unique pattern of different ecosystems shared with neighbouring countries. Pollen records are found throughout a wide range of biomes and elevations (Flantua et al., 2015a), from the tropical rainforest and mangroves along the coast to the high Andean "páramos". The complex formation of the Andes with the three mountain ridges characterizes this region with numerous valleys and watersheds.

A total of 64 records are available that present pollen data within the last 2 ka. Of this number, 21 fulfilled four of the PAGES-2 k criteria, another 24 fulfilled three criteria, and the remaining records presented at least two dating control points within the last 2 ka. Unfortunately, 14 were presented in publications without a peer-review procedure or presented only as a summary diagram (7 records with four positive criteria). An additional 5 records which fulfilled all criteria suggested human presence during most part of the last 2 ka, and were therefore excluded for climate reconstructions. From the remaining records, only lakes `Pallcacocha` and `Papallacta PA1-08` in Ecuador lack human interference during the last 2 ka. The others describe human indicators over limited periods of time and are considered valuable for PAGES-2 k purposes. Most of the records complying with three criteria ($n = 24$), most of them identify human presence in the near surrounding of the record during a reasonable period of time, leaving only `ECSF Refugio` potentially suitable for 2 ka climate reconstructions.

Beginning at the far N of the region (Fig. 6b and Fig. 8), `Lake Valencia` is represented by three cores with varying quality in chronology and resolution. In spite of the low resolution sampling (10–14 samples for the last 2 ka), some general information can be derived from the joint interpretation of these three cores. The last 2 ka are characterised by a decline of forest cover, attaining the lowest values of the Holocene, at the expense of savannas. Aquatic proxies indicate declining lake levels and increasing nu-





CPD
11, 3475–3565, 2015

trient input, a trend that accelerated during the last 0.5 ka, when human activities were more intense around the lake. Considering the entire Lateglacial–Holocene record, the `Lake Valencia` catchment has shown to be more sensitive to moisture variations than to temperature, as known from tropical lowlands.

In the Andean region, changes of the altitudinal position of the upper forest line (UFL) are instrumental in reconstructing temperature changes. This ecotone is defined as the highest elevation contour of continuous forest and marks the boundary between the forest and high Andean páramo biome (Moscol-Olivera and Hooghiemstra, 2010; Groot et al., 2013). The Andean sites in Venezuela and Colombia show indications of colder climates by decreased forest pollen at higher elevations. In the Venezuelan Andes, the only available pollen record is `Piedras Blancas`. There is no indication of human activity; hence changes should be attributed mostly to climatic shifts, notably temperature and moisture. Expansion of superpáramo vegetation suggests a response to the Medieval Climate Anomaly (MCA, ∼ 1.15–0.65 ka), while a period of scarce vegetation could be related to the LIA (∼ 0.6–0.1 ka). The absence of tree pollen in several samples indicates significantly depressed UFL in comparison to today.

Along the transitional zone between savanna and tropical rainforest in the eastern Colombian savannas, three pollen records fulfil at least three criteria. This climate-sensitive transition zone is thought to reflect precession-forced changes in seasonality, latitudinal migration of the ITCZ, and changes in the ENSO (Figs. 3 and 4; Wille et al., 2003). Since 2 ka gradual increase in savanna vegetation is observed, suggesting a period of progressively drier conditions, e.g. `Loma Linda` and `Las Margaritas`). However, expanding *Mauritia* palm forest during this period was observed in several records considered to reflect increased local water availability and precipitation (Fig. 8b), and/or human impact (Rull and Montoya, 2014).

Along the N Andean Pacific slopes, `Jotaordó`, `El Caimito`, `Guandal` and `Piusbi` document vegetation changes related to the precipitation regime in the C and S Chocó biogeographic region. Settings differ, as the first is located in a broad river valley with a meandering drainage system while `El Caimito` and `Guandal` are lo-



CPD
11, 3475–3565, 2015
Climate variability and human impact in South America during the last 2000 years
S. G. A. Flantua et al.

cated in the coastal plain receiving signals from shifting mangrove forests. These shifts were considered not to be climate related but explained by tectonic events in the region and/or dynamic shifts of the river deposition patterns. Frequent erosion events, various seismic shifts and disturbance indicators from mixed origin during the last 2 ka hinder consistent conclusions for the region. Changes in vegetation composition around 0.65 ka were assigned in `El Caimito` to reduced flooding and possible human intervention, while similar changes at `Jotaordó` were ascribed to endogenous dynamics. Only the multi-proxy approach of `El Caimito` suggests a possible relationship between periods of higher riverine dynamics and the frequency of long term ENSO variability. Interestingly, within this region *Cecropia* is used as natural disturbance indicator due to fluvial-marine dynamics, while in the other Colombian regions this fast-growing species is considered characteristic of human interference: both settings have disturbance as a common factor.

In the Colombian Andes there are no undisturbed pollen records during the last 2 ka suitable for climate reconstructions. Before the human disturbances, the `La Cocha-1` record in the far S of Colombia (Fig. 8b) indicated generally wetter conditions similar to the N Ecuadorian pollen records of `Guandera-G15` and `Guandera-G8`. Andean records can display dissimilar timing and trends behaviours due to differences in precipitation along the eastern Andean flank and specific regional landscapes (Moscol Olivera and Hooghiemstra, 2010; Marchant et al., 2001). A different kind of index to highlight vegetation-climate interaction was used in the eastern Ecuadorian Andes at `Papallacta PA1-08`. Established to characterize the SASM and ENSO, the index interprets cloud transported forest pollen taxa and Poaceae as a proxy for upslope cloud convection. Supported by a high resolution ($\sim$ 15 year), a high frequency of dry and humid episodes is detected during the last 1.1 ka. In this alternation of convective activity, the MCA, LIA and current warm period are considered detectable.

In S Ecuador 4 pollen records suitable for PAGES-2 k purposes are found within a relatively small sub-region. `Tres Lagunas` suggests a cold phase, possibly the LIA, as one of several warm and cold phases detected during the last 2 ka (Fig. 8b).





CPD
11, 3475–3565, 2015

Cold and moist conditions are related to high abundances of Poaceae, *Isoëtes* and *Gentianella*. At Laguna Zurita, the decrease of *Isoëtes* was considered an indication of increased precipitation after ∼ 1.2 ka, observed similarly in other fossil pollen records in the C Peruvian Andes. On the other hand, chemical analyses from the same core suggested drier conditions during the last millennium, confirmed by a different set of palaeoclimatic records. Unknown human interference in the last millennium could be related to these divergent patterns, as the nearby ECSF Refugio and Laguna Daniel Álvarez detected *Zea mays* around 1.4 and 0.8 ka respectively. Climate was considered to be drier overall before 1.2 ka.

### 4.3 Climate–vegetation interaction in the central Andes

The C Andes includes the high elevation plateau of the Altiplano, above 3000 m a.s.l., in S Peru, Bolivia and N Chile (Fig. 6c). The Altiplano is an area of internal drainage within the Andes that contains multiple peaks over 5000 m a.s.l. The vegetation of the Altiplano is characterized by different grassland types, collectively known as "puna" (Kuentz et al., 2007). Within the grassland matrix are patches of woodland dominated by trees of the genus *Polylepis* (Fjeldså and Kessler, 1996). To the E and W of the Altiplano are the steep flanks of the Andes.

In total 57 pollen records covering the last 2 ka were identified from the Altiplano in Peru and Bolivia. Only 4 of the Altiplano records met all PAGES-2 k criteria: (i) Cerro Llamoca, (ii) Marcacocha, (iii) Chicha Soras, and (iv) Pacucha (Fig. 9a; Table 3). From the surrounding regions 2 additional records are also considered here because of their importance and fit to the PAGES-2 k criteria: (i) Consuelo on the eastern Andean flank, at mid-elevation (1370 m a.s.l.) within the cloud forest fulfils two of the criteria, while (ii) Urpi Cocha on the Pacific coast at sea-level, ∼ 1 km inland within the archaeological site of Pachacmac (near Lima), satisfies four of the criteria. Of the seven sites considered in this review during the last 2 ka: 2 records (Cerro Llamoca and Consuelo) show no human interference, 1 record (Chicha-Soras) indicates humans from 1.5 ka onwards, and the other 4 (Marcacocha, Pacucha, Nevado Coropuna, and Urpi Cocha) indicate human impact throughout the last 2 ka.

Discerning a climate signal from the pollen records of the last 2 ka in the C Andes is a challenge due to the long legacy of human occupation and landscape modification (Bennett, 1946; Dillehay et al., 2005; Silverman, 2008). However, some idea of vegetation–climate relationships can be gained from modern pollen studies within the Puna, e.g. Kuentz et al. (2007) use the ratio of Poaceae:Asteraceae (Coropuna), or Schittek et al. (2015) focus on the abundance of Poaceae (Cerro Llamoca) as an indicator of moisture availability. In the other records, where there is no direct relationship between vegetation and climate discernible, some authors look at the relationship between the pollen records and other indicators to disentangle climate and human induced vegetation change; such as independent evidence of farming activity (e.g. oribatid mites), or association with archaeological evidence for abandonment/occupation (Chepstow-Lusty, 2011).

The two records considered here that are purported to have no local human impact (Cerro Llamoca and Consuelo) provide the best opportunity of extracting a clear insight into past climatic change in the C Andes during the last 2 ka. The record from Cerro Llamoca (4450 m a.s.l.) indicates a succession of dry and moist episodes (Fig. 9b). After 0.5 ka sediments at Cerro Llamoca are composed of re-deposited and eroded material and consequently interpretation of the latter half of the record is difficult. In contrast little compositional change is evident in the Consuelo record, with the most significant variance during the last 2 ka being a rise in *Cecropia* sp. pollen after 1 ka. *Cecropia* pollen is typically interpreted as an indicator of disturbance (Bush and Rivera, 2001) and therefore, in the absence of humans signal, the rise in *Cecropia* could be interpreted as an elevated level of natural disturbance. The switch to very dry conditions at Cerro Llamoca in the western Andean cordillera and the rise in *Cecropia* at Consuelo on the E Andean flank are broadly coincident (~ 0.85 ka); however, it is not possible to say if this pattern results from a common climatic mechanism.





CPD
11, 3475–3565, 2015

Archaeological evidence from Chicha-Soras (∼ 3500 m a.s.l.) does not show any evidence of human occupation of the valley between ∼ 1.9 ka and ∼ 1.4 ka. Between 1.4 and 1 ka and between 1 and 0.65 ka, high abundance of Chenopodiaceae/Amaranthaceae (Cheno/Am) could be interpreted as either indicating arid conditions or expansion of *quinoa* crops (Ledru et al., 2013). However, a drop in charcoal fragments (fire activity) coupled with the absence of archaeological evidence (∼ 1.9–1.4 ka), suggests that people abandon the valley during 1.5–0.5 ka and, consequently, that the aridity signal from the pollen could be interpreted as a climatic one.

Some climate information has been inferred from the four remaining sites (Marcacocha, Pacucha, Nevado Coropuna and Urpi Cocha) despite the strong human influence over the vegetation. At Nevado Coropuna humid conditions persisted until a short dry episode occurred 0.97–0.82 ka (Fig. 9b). During the last 2 ka at Marcacocha (3300 m a.s.l.) successive peaks in Cyperaceae pollen have been interpreted as indicative of three periods of elevated aridity while elevated *Plantago* at ∼ 1.9 ka is suggested to indicate cooler conditions, and *Alnus* at ∼ 1–0.5 ka could indicate warmer and drier conditions (Chepstow-Lusty et al., 1996); although discerning the climate signal related to *Alnus* is difficult due to its utilisation in agro-forestry practices (Chepstow-Lusty and Jonsson, 2000). At Pacucha and Urpi Kocha significant changes to the pollen assemblage in the last 2 ka are attributed to human activity rather than climate.

Generally the pollen records from the Altiplano tend to show a greater sensitivity to precipitation, rather than temperature. The greater sensitivity to precipitation is because moisture availability is in most areas the limiting factor for both vegetation communities and human populations. However, two records infer significant changes in temperature related to vegetation/human occupation: (1) Marcacocha when the sudden stop in agricultural activities is attributed to colder temperatures, and (2) at Coropuna when the increase of human occupation (expansion of Inca culture) at higher elevation shows that there was no glacier and warmer temperatures. On the Altiplano variation in the SASM has been attributed as a major driver of changes in moisture balance at Llamoca, Coropuna, Pacucha through altering the summer precipitation. SASM is also thought to be responsible for precipitation variation on the E Andean flank (Consuelo), while on the western Andean flank (Urpi Cocha) precipitation variation is attributed to the ENSO through tsunamis and the abrupt floodings on the Pacific coast. Although the pollen records of the Altiplano are likely to be somewhat obscured by the agricultural activities and irrigation of the crops all the records point towards a dry event occurring roughly between 1.2 and 0.75 ka.

### 4.4 Climate–vegetation interaction in the Lowland Amazon Basin

For the purpose of this review, the Lowland Amazon Basin constitutes those regions of the Amazon drainage < 500 m a.s.l. and extends to the lowland Guianas (Fig. 6d). This encompasses the evergreen rainforest, which covers most of Amazonia, as well as the S transitional/seasonally-dry tropical forests located in NE Bolivia and S Rondônia, N Mato Grosso and N Para State, Brazil. It also includes the Llanos de Moxos savannas of NE Bolivia, the ecotonal rainforest-savanna areas of N Roraima State, Brazil, and extends to the coastal swamps/grasslands of N Brazil and French Guiana.

In total 42 published pollen records that cover the last 2 ka were identified from the Lowland Amazon Basin. Only 5 records complied with all four of the criteria and 11 records met with three criteria (Table 3). Most of the remaining records span a period ≥ 0.5 ka, but do not meet with any of the other criteria. One of these records, lake La Gaiba, is situated just outside the Amazon Basin, in the Pantanal region of central Brazil/SE Bolivia. However, the record and its hydrological catchment reflect Holocene precipitation in the S Amazon Basin (Whitney et al., 2011), and therefore was included as part of this review.

By applying the dating constraints of the PAGES-2 k criteria, the majority of pollen records from the Amazon Basin are discounted from any analysis of climate–vegetation interaction for the past 2 ka. However, 5 records were found to meet the criteria: Quistococha, Werth, Granja, Fazenda Cigana and French Guiana K-VIII (Table 3, Fig. 10a).





CPD
11, 3475–3565, 2015

Lake Quistococha in the NE Peruvian Amazon is an infilled river channel surrounded by *Mauritia flexuosa*-dominated palm swamp. Vegetation has undergone several significant species compositional changes over the past 2 ka. The broad pattern of vegetation change was from *Cecropia*-dominated riverine forest at ∼ 2.2 ka, to abundant Cyperaceae and floating grasses/ferns and the commencement of peat formation ∼ 2.1 ka, then to seasonally-inundated riverine forest, with abundant Moraceae and Myrtaceae from ∼ 1.9 ka, and finally, the development of closed-canopy, *Mauritia*-dominated swamp from ∼ 1 ka until present. Superimposed on this broad pattern of change were rapid, centennial-scale shifts in forest composition and degree of openness. However, these rapid shifts were attributed by the authors to hydrological dynamics, rather than climate change or human impact.

Lake Werth belongs to a collection of sites (also Gentry, Vargas and Parker) in the "Madre de Díos" region of the SE Peruvian Amazon. Site Werth is surrounded by humid evergreen rainforest. The lake formed ∼ 3.4 ka and records continuous evergreen rainforest throughout, with little evidence of burning. The records from the surrounding three lakes concur, suggesting that, regionally, rainforest (and climate) has been stable over the last 2 ka.

Laguna Granja is located on the edge of the Pre-Cambrian Shield in NE Bolivia. Its location is at the margin of the modern Madeira-Tapajós rainforest ecoregion, which extends southwards from the main Amazon River to the southern margin of the Amazon Basin in Bolivia (Olson et al., 2010). The record has a maximum age of 6 ka and indicates that savanna characterised the landscape around Granja from 6 ka. This is in agreement with a regional scale reconstruction from the much larger Lake Orícore (not shown, Carson et al., 2014), which is located < 20 km away from Granja, and shows climate-driven expansion of evergreen rainforest in this region between ∼ 2 and 1.7 ka. However, forest expansion does not occur on the Granja site until 0.5 ka. The distribution of forest vs. savanna around Granja was shown to be heavily influenced by human land use between 2.5 and 0.5 ka (Carson et al., 2014, 2015), therefore, it is not suitable for analysis of naturally-driven vegetation dynamics.





CPD
11, 3475–3565, 2015

The `Fazenda Cigana` record is derived from a palm swamp in the savanna-gallery forest mosaic landscape of N Roraima State, in the N Brazilian Amazon. The core was taken as one of a pair, along with the `Terra Indígena Aningal` record, which was cored from the same *Mauritia* swamp. The pollen records are dominated by *Mauritia* throughout, which the authors attribute to continuously wet climate in this region in the late Holocene. There are however centennial-scale periods of gallery forest reduction and grassland expansion, accompanied by increased charcoal concentrations. Da Silva Meneses et al. (2013) infer that these periods of high burning were anthropogenic in origin, and compare them to modern day prescribed burning practices used by indigenous people in the northern Amazon to maintain an open savanna landscape. Despite the potential human interference, these records demonstrate natural stability of the forest-savanna ecotone over the last 1.5 ka in this particular part of the N Amazon.

The *French Guiana K-VIII* record is situated in from the coastal wetland savanna of French Guiana. The record was taken within a landscape of pre-Columbian mounded agricultural fields, with the principal aim of investigating ancient human land use associated with these earthworks on a local scale. From this earliest part of the record, the fossil pollen spectra indicate seasonally-inundated savanna, dominated by Cyperaceae and Marantaceae until 0.8 ka when human inference is detected. In the post-European period after ~ 0.5 ka, however, charcoal abundance increases, probably reflecting more intensive use of fire by colonial populations. This again is a record that reflects substantial anthropogenic impact on the landscape, and is therefore not suitable as an independent proxy record of climate-induced vegetation change; at least not within the last ~ 0.8 ka.

### 4.5 Climate–vegetation interaction in Southern and Southeastern Brazil

The vegetation in S-SE Brazil includes forest ecosystems such as the tropical Atlantic rainforest, Araucaria forest, semi-deciduous forest, “Cerrado” (savanna woodland) and different grassland ecosystems such as “Campos” and “Campos de Altitude” (high elevation grassland) (Fig. 6e). The Atlantic rainforest occurs in S-SE Brazil as a 100





CPD
11, 3475–3565, 2015

to 200 km narrow zone in the coastal lowlands along the Atlantic Ocean, and on the coastal eastern slopes of the mountain ranges. The tropical semi-deciduous forest occurs further inland in SE Brazil. The Cerrado is found primarily in C Brazil, but also in the N part of SE Brazil. The subtropical grasslands are found in highland S Brazil and lowlands of the southernmost region of S Brazil. Additional background information is provided in the Supplement.

There are approximately 50 pollen records known from S-SE Brazil, but many sites have not been published in peer-reviewed journals and were therefore not considered. Unfortunately, the 2 records that agree with all criteria, show human interference (Table 3). Therefore a general overview of climate–vegetation interaction from the region are presented, considering the 7 records sites that fulfil some of the criteria (Table 3, Fig. 11a).

Sites located in the mountains of S-SE Brazil and from the transition area between the subtropics and tropics are sensitive to both temperature and precipitation, e.g. the length of the dry season is considered to play an important role. In S Brazil pollen records indicate vegetational changes that reflect a change from relatively dry climate during early and mid Holocene to wetter conditions after about 4.3 ka, and in particular after 1.1 ka (Fig. 11b). Increasing moisture is clearly indicated on the S Brazilian highlands by the expansion of *Araucaria* forests in form of gallery forests along rivers and a pronounced expansion of *Araucaria* forest into the Campos after about 1.1 ka (e.g. `Cambara do Sul` and `Rincâo das Cabritas`). The expansion of gallery forests at similar time periods (5.2 and 1.6 ka, respectively) is also recorded in the southernmost lowland in S Brazil by the `São Francisco de Assis` record. Study sites that reflect changes in the Atlantic rainforest area indicate an expansion during the Holocene where overall wetter conditions prevailed compared to highland and southernmost lowland areas, e.g. `Ciama 2` (Fig. 11b).

In contrast to other sites and regions, a relative humid and warm phase during the LIA is interfered from the high resolution `Cambara do Sul` record as an expansion of *Weinmannia* in the Araucaria forest is observed. In SE Brazil the `Lago do Pires` and

Lagoa Nova record indicate that a dense and closed semi-deciduous forest existed in the region only in the late Holocene period under the current climatic conditions with a ∼ 3 month dry seasons. In the mountains of SE Brazil (e.g. Serra dos Orgâos record) a reduction of Campos de Altitude occurred 0.9 ka indicating a change to wetter conditions that is broadly coeval with a similar trend in the Lago do Pires record (Fig. 11b).

### 4.6 Climate–vegetation interaction in Pampa plains

This region extends E of the Andes, between 30 and 40° S (Fig. 6f) and is characterized by dominant aeolian landforms marking the structural characteristics of the subsurface geology and climatic gradient of the landscape (Zárate and Tripaldi, 2012). The natural vegetation of the Pampa is a tree-less grassland. Potential vegetation units can be characterized as: E Pampa, inland Pampa and S Pampa, based on phytosociological characteristics, historical observations on land use, and climatic and geomorphological differences (Tonello and Prieto, 2008; Supplement). The region has a relatively short farming history, since most of the area remained as native grassland until the end of the 19th and the beginning of the 20th century (Viglizzo and Frank, 2006). Today, only around 30 % of the region is covered by natural or semi-natural grassland.

In total 9 pollen records were assessed for the last 2 ka. All four dating criteria were met in one record only (Lonkoy) and three criteria were matched at Sauce Grande (Table 3). The pollen record of site Hinojales-San Leoncio does not fulfil the four dating criteria, however the record shows important hydrological signals for the last 2 ka and is therefore briefly discussed (Fig. 12b).

Aquatic ecosystems are considered sensitive to climatic and/or hydrological variations, and exhibit frequent fluctuations in their water level and extension, leaving flooded or exposed plains. The multi-proxy approach allows the identification of responses to natural and/or anthropogenic forcing factors. Pollen together with non-pollen palynomorphs and plant macrofossil analysis present similar trends in SE Pampa that support climate to be a regional trigger of change (Stutz et al., 2015). From 2 to 0.5 ka





CPD
11, 3475–3565, 2015

an instable regional environment with drier climatic conditions than present are inferred from the region, based on halophyte plant communities (Chenopodiaceae) surrounding the lakes whereas *Chara* and other aquatic plants (e.g. *Myriophyllum*, *Potamogeton*) characterized the water bodies. Towards ∼ 0.5 ka vegetation switched to Cyperaceae dominance and aquatic plants similar to modern community. Thus, turbid conditions with higher water level and/or extension of surface lakes under more stable environmental conditions are inferred. These support humid conditions similar to present with a noticeable increase of precipitation after 0.3 ka, indicated by high Cyperaceae abundances. However, a integrative multi-proxy approach allow inferring stable conditions and higher salinity values between 1.9 and 0.9 ka and periods of water level fluctuations after 0.9 ka, with high water levels between 0.66 and 0.27 ka. These changes may have been caused by fluctuations in precipitation (Fontana, 2005).

### 4.7 Climate–vegetation interaction in the Southern Andes and Patagonia

The study area comprises the S Andes, which includes subtropical and temperate regions (22–56° S) on both sides of the Andes, including Patagonia (40–56° S) which extends from the Andes eastwards to the Atlantic Ocean (Fig. 6g). The region has different geomorphological settings associated with glacial, volcanic and tectonic activities. Vegetation associations reflect the W–E precipitation gradient from the wet *Nothofagus* forest to the dry grass and shrub steppe towards the Atlantic coast. The S–N gradient along the Andes ranges from the *Nothofagus* temperate forest in the austral region to the *Nothofagus*-*Astrocedrus* forest, sclerophyllous forest and xerophytic woodland in the C region. In the northernmost end of the latitudinal gradient, the vegetation is adapted to extremely arid conditions characterized by small and dwarf shrubs and scarce cover (Supplement). Anthropogenic activities during the last century have caused a range of disturbances (e.g. fire, forest clearance, grazing, agriculture) and major vegetation changes in forest and steppe areas have occurred.

In this region, there are 48 pollen records that cover the last 2 ka with at least one chronological control point during this period. Of these, the 19 records that fulfil





CPD
11, 3475–3565, 2015

PAGES-2 k criteria are mostly concentrated in the temperate forests, while only few originate from xerophytic shrub steppe (1 record), subtropical forest – sclerophyllous forest (2 records) and grass steppe (4 records) (Table 3; Fig. 13a).

At the most southerly sites, the "Tierra del Fuego"s `Onamonte mire` (54° S) located at the *Nothofagus* forest-grass steppe ecotone shows a gradual *Nothofagus* forest development between 1.5–0.5 ka followed by a major forest development up to the present, reflecting increased precipitation (Fig. 13b). `Puerto Harberton` (55° S) at the mixed *Nothofagus betuloides–N. pumilio* forest shows *Nothofagus* dominance during the 2 ka, whereas the *Ericaceae* increase during the last 1 ka suggests local decrease of the water table. Similarly, at `Valle de Andorra` (54° S) in *Nothofagus pumilio* forest, *Empetrum/Ericaceae* fluctuations reflect changing water tables.

In S Patagonia (52–51° S) along E Andes, there are several sites at or near the forest-steppe ecotone. Of these ecotonal sites, `Rio Rubens` (52° S) shows a closed *Nothofagus* forest until 0.4 ka when European impact starts (Fig. 13b). Similary, `Lago Cipreses` (51° S) and `Lago Guanaco` (51° S) show dominance of *Nothofagus* forest, but with increase of non-arboreal pollen (and decrease of *Nothofagus*) associated with a reduction of precipitation induced by the Southern Westerly Wind Belt (SWWB) and the Southern Annular Mode (SAM) phases. Furthermore, changes associated to dry/warm climate conditions appear to synchronize with N hemispheric events such as the Industrial Revolution, MCA, Roman Warm Period and Late Bronze Age Warm Period (Moreno et al., 2014), that alternate with wet/cool phases. `Cerro Frias` (50° S) shows open forest from 2.0–0.9 ka, followed by prevalent grass steppe that is punctuated by an increase in *Nothofagus* at 0.016 ka. Estimates of annual precipitation suggest similar or higher values than modern between 2–1 ka, lower values between 0.9–0.015 ka, followed by similar-to-modern precipitation in the last 0.015 ka. Currently located in mixed deciduous *Nothofagus* forest, the `Peninsula Avellaneda Bajo` (50° S) records an open forest from 2 ka, of which large expanses were replaced by grass steppe between 0.4–0.2 ka, associated with a decline in precipitation.





CPD
11, 3475–3565, 2015

In C Patagonia (47–44° S) pollen records are located at the E of Andes (Fig. 13a). At Parque Nacional Perito Moreno (47° S) a shrub-steppe expansion (Asteraceae and *Embothrium* dominance) suggests lower precipitation values between 1.2 and 0.25 ka compared to previous values, after which an increase in grass-steppe occurs due to higher moisture availability (Fig. 13b). However, the Mallin Pollux (45° S) record indicates an open canopy prior to 1.5 ka followed by a *Nothofagus* forest expansion associated to precipitation increase. Mallín El Embudo (44° S) within *Nothofagus* deciduous forest, shows unvarying forest composition during the last 2 ka. Located in the same valley, the Lago Shaman (44° S) record (*Nothofagus* forest-steppe ecotone) shows a more diverse pattern throughout the last 2 ka, with a forest retraction at ~ 1.7 ka, followed by an expansion around 1.5–1.3 ka and a major forest development around 0.5 ka. The forest decrease during the last 0.2 ka is associated to human intervention.

In N Patagonia (44–38° S), Lago Mosquito (42° S) is the only record in E Andes and it is located at the transition between *Austrocedrus* woodland and shrubland-steppe. The record shows an open *Nothofagus-Austrocedrus* forest with elements of steppe and grassland elements between 2–1.4 ka, changing to higher *Nothofagus* forest dominance, which is attributed to wetter conditions (Fig. 13b). From 0.225 ka to the present, *Nothofagus* shows a sharp decrease and *Cupressaceae* increases, together with rising introduced species, e.g. *Rumex* and *Pinus*. At the same latitude, Lago Lepué (42° S) located in the Isla Grande de Chiloé and surrounded by evergreen rain forest, shows dominance of *Nothofagus* during the last 6k with an important reversion between 2–0.8 ka. This suggests a lower precipitation than before and after 0.8 ka, shown by an increase of *Weinmannia* and *Isoëtes*. Lago Pichilafquen (41° S) record, under the domain of the SWWB and influenced by the Subtropical Pacific Anticyclone in summer, shows a series of warm/dry and cold/wet phases for the last 2 ka (Fig. 13b). These phases are inferred by the varying abundances of *Nothofagus* and *Eucryphia*/*Caldcluvia* and Poaceae. The last centuries are characterized by human intervention. At the temperate-subtropical transition, Laguna San Pedro (38° S) record





CPD
11, 3475–3565, 2015

shows dry-warm phases which were associated with the MCA period. Cold and wet conditions, inferred by the relation between *Nothofagus* and Poaceae, and changes in the depositional time, prevailed during the LIA, possibly related to El Niño and La Niña influencing these wet and dry phases respectively (Fig. 5).

To the N (westward Andes), the `Lago Aculeo` record (34° S) shows dominance of Poaceae dominance suggesting relatively steady conditions during the last 2 ka with expection of last 0.1 ka, when a trend towards warmer conditions or human disturbance is reflected by increase in Chenopodiaceae (Fig. 13b). Interestingly, the sedimentary record shows a series of turbidite layers associated with major ENSO frequency between 1.8–1.3 ka and 0.7–0.3 ka (Jenny et al., 2002). The `Palo Colorado` (32° S) record shows dominance of Myrtaceae associated with wet conditions during last 2 ka alterating with several dry pulses. A major dry peak at 0.4 ka may be related to climate and/or human activity. Similarly at E Andes, `Abra del Infiernillo` (26° S) shows an increase in moisture between 2–0.75 ka inferred from Juncaceae, Poaceae, Cyperaceae and Pteridophyta pollen; and a change to dry climatic conditions similar than modern from 0.75 ka on.

`Lago Potrok Aike` and `Lago Azul` (both 52° S) show a dominance of Poaceae since 2 ka, with long-distance transported pollen of *Nothofagus*. At `Potrok Aike`, reconstructed annual precipitation based on transfer function indicates rising values during the last 2 ka (Fig. 13b). `Cabo Vírgenes` (52° S), located at SE Patagonian grass steppe, shows a shrubland community between 1.2–0.7 ka, associated with drier conditions than at present. An increase in moisture after ~ 0.7 ka is indicated by Poaceae and Juncaginaceae pollen. `Cabo Vírgenes CV22` shows a similar trend, with dry grass-shrub steppe between 1.05–0.6 ka, followed by a grass-dominated steppe suggesting higher moisture availability.

### 4.8 Indicators of human land use in 2 ka pollen records

In general, indicators of human activities in pollen records are decrease in forest taxa (degraded forest) and/or forest representation (deforestation), presence of crops like



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

*Zea mays, Manihot esculenta, Phaseolus* and *Ipomoea*, crop-related herbs *Rumex*, increase of grasses/herbs like Poaceae, Cyperaceae and Asteraceae subf. Cichorioideae, increase of disturbance indicators like Cheno/Am, *Cecropia, Vismia*, ferns and palms (e.g. *Mauritia* and *Euterpe/Geonoma*), and presence of charcoal peaks due to anthropogenic fire (Fig. 14). *Manihot esculenta* and other crops such as *Zea mays* are considered direct indicators of human influence and provide clear evidence of land use. Indirect indicators such as change in forest composition (e.g. due to deforestation) or species known as disturbance indicators (*Cecropia* and *Mauritia*) need additional proxies to derive conclusive findings. Only by looking at pollen changes in context with other evidence – e.g. charcoal, limnology, sedimentology, archaeology- can the correct origin of these changes be identified.

In any palaeo-reconstruction concerning the past 2 ka, human land use must be considered as a potentially important agent of environmental change. However, where there is no direct evidence of human land use, such as cultigen pollen, distinguishing natural from anthropogenically induced burning and vegetation change can be difficult. Similar to human indicators in pollen records, complementary paleo-proxies can support more confident interpretation. This further highlights the difficulty of inferring climate-induced vegetation changes, without reference to independent climate proxy data, such as geochemical records from speleothems.

To date, major human impact in the Venezuelan Guayana uplands has been suggested for the last 2 ka and inferred from the charcoal record, without any evidence of crops. Compared to the highlands (1500–3000 m a.s.l.), the situation in the uplands (500–1500 m a.s.l.) differs substantially as fire is maximally responsible for vegetation change during the last 2 ka. The `Urué` record shows the consequence of repeated burning upon the vegetation, preventing the recovery of pre-existing forests and allowing the appearance of a "helechal" (fern-dominated vegetation; Huber and Riina, 1997), and finally the establishment of the savanna. The occurrence of high fire regimes during the last 2 ka is a common feature of mostly all the upland records analysed so far, regardless the plant association present at each location. Synchronous with this in-





CPD
11, 3475–3565, 2015

crease in fire regime, those records that nowadays are characterised by *Mauritia* palm swamps, showed parallel a sudden appearance and establishment of *Mauritia*. Human activities have been proposed as the likely cause of this high abundance of fires, and thereby of the consequences that produced upon the landscape. In this sense, the repeated use of fires would have promoted the reduction of forests and expansion of the savanna, favouring the establishment of *Mauritia* swamps after clearing. Two records are particularly relevant regarding the human influence on the Venezuelan Guayana uplands. `Lake Chonita` sequence (Table 3) registered among the earliest *Mauritia* establishment coeval with a significant increase in the fire regime during a likely local wet period around 2 ka. In the southernmost boundary of the Venezuelan Guayana, `El Paují` (Table 3) was interpreted as potentially reflecting human activities since the mid Holocene. This location is characterised today by treeless savanna surrounded by dense rainforests that established ∼ 1.4 ka as shown by the highest abundance of algal remains (local wet conditions) and charcoal particles (fire regime). The establishment of the present-day landscape was interpreted as mainly anthropogenically driven, with the arrival to the study area of the current inhabitants. The occurrence of a previous secondary dry forest was interpreted as the result of climate-human interplay, linking land abandonment and likely drier climate as the main responsible favouring the vegetation shift. From the Colombian savannas, human occupation is attested since the mid Holocene (Berrio et al., 2002). At site `Loma Linda` a plausible signal of human interference in the last 2 ka is shown by increased savanna, although precipitation increase during the same period (Marchant et al., 2001, 2002) could be interfering with that signal.

The human history in the N Andean region goes back to the Lateglacial (Van der Hammen and Correal Urrego, 1978). The high plains of the Colombian Cordilleras provided suitable conditions for human settlements since the start of the Holocene. Increasing human occupation became evident in pollen records after ∼ 3 ka, such as `Fúquene-2` (Van Geel and Van der Hammen, 1973) and `Pantano de Genagra` (Behling et al., 1998b). In several Andean diagrams, *Rumex* marked the onset of more intense land use by Europeans since 0.4 ka (Bellwood, 2004). Before these dates, indigenous populations were scarce and their practices negligible in terms of impact, especially at high elevations sites such as Piedras Blancas in Venezuela.

In the C Andes a high level of human activity, spatially variable in intensity, has been shaping the landscape for the last 2 ka. Cheno/Am and *Zea mays* generally appear in all the records in the central Andes after 4 ka, e.g. Pacucha, Marcacocha, Chicha-Soras and Urpi Kotcha. After 2 ka, *Alnus* and agroforestry practices are observed (Marcacocha, Pacucha). When irrigation started to be developed in sites without a nearby lake as for instance ~ 1 ka at Coropuna, *Ambrosia* may be used as a terrace consolidator.

Evidence of afforestation in two sites with high human influence (Marcacocha and Pacucha) are observed. Indeed *Alnus acuminata* is a tree planted by the Inca to stabilise landscapes (Chepstow-Lusty, 2011). At lower elevation, in the Andean forest, the last 2 ka pollen data indicate little change in woodland cover which remains high on the eastern Andean flank (Consuelo), and low in the west (Urpi Kocha; 52 m a.s.l.).

In the tropical lowlands along the Pacific coast, increases in the presence of palms (mainly *Euterpe/Geonoma*), are commonly interpreted as a result from more intensive forest use, e.g. Lake Piusbi (Behling et al., 1998a). Pollen grains from crops like *Zea mays, Phaseolus* and *Ipomoea* are found in Piagua (Vélez et al., 2001). Human disturbance to the forest is considered indicated by high percentages of abundance of *Cecropia*, ferns and palms. Decreases in human impact during the last 2 ka has been described by sites like Pitaliton, Timbio, La Genagra, Quilichao and La Teta, as grassy vegetation (Poaceae) and *Zea mays* disappeared and forest started to recover. This vegetation change could be related to the first arrival of the Spanish "conquistadors" (González-Carranza et al., 2012), or a set of different causes (Wille and Hooghiemstra, 2000).

Of the 42 pollen records identified from the Lowland Amazon Basin, 15 show evidence of pre- and post-European land use within the last millennia. Human land use is inferred from these records from cultigen pollen grains, charcoal and forest clearance





CPD
11, 3475–3565, 2015

(Table 3). In some cases there is also archaeological and archaeobotanical evidence for human land use. At many of the sites occupied by native Amazonians, evidence of land use as a decline in burning by or before 0.5 ka, probably in relation to first European contact. However, some sites, such as `French Guiana VII` and `Granja` show evidence of continued post-European land use.

Pampa vegetation does not show evidence of human impact prior to European settlement at 0.4 ka. Europeans introduced several tree species (e.g. *Eucalyptus*, *Pinus*), as well as cattle (cow and horse) and crops (wheat, sunflower), but the intensive agricultural activities only began 0.05 ka (Ghersa and León, 2001). The paleoenvironmental history of shallow lakes shows a change to more productive systems (higher mass of phytoplankton and organic matter content) during the last 0.1–0.08 ka probably due to agricultural activities. On the other hand, pollen records show an increase of pollen types associated with overgrazing (*Plantago* and/or Asteraceae Asteroideae) and exotic trees during the last 0.1 ka.

In S Andes and Patagonia, there is not conclusive evidence of native human activities in the pollen records and native-fire disturbance has been long discussed. Charcoal records from E Andes have not revealed fire activity associated with native populations. A probable explanation for this lack of evidence is a low density of populations associated with sporadic forest impact (Iglesias and Whitlock, 2014). In general, human activities indicators are forest decrease, presence of exotic pollen types (e.g. *Rumex*) and increase of some pollen types (e.g. Asteraceae subf. Cichoroideae, Chenopodiaceae) associated to European presence in the region. The time of colonization varied among S Andes and Patagonian sites, but ∼ 0.1 ka can be considered the start of European activities in Patagonia. Differences in timing of the first appearance of human indicators in pollen records could reflect European settlement dynamics, with earlier presence in more northerly sites and later more isolated areas (in the south of continent). The first human indicator is recorded at `Rio Rubens` (52° S) with the appearance of the European weed pollen *Rumex acetosella*-type appearance in the early European era (∼ 0.3 ka).





CPD
11, 3475–3565, 2015

## 5 Discussion of the regional assessments

### 5.1 General observations for 2 ka pollen compilations

This review reveals that those records with better dating resolution in the late Holocene (e.g. `Granja, French Guiana K-VIII` in the Amazon Basin) are often from cores that span a shorter time period, while longer temporal records have less well resolved Holocene chronologies. This likely reflects (i) the need to spread limited numbers of radiocarbon dates in order to provide robust age models for these deeper time records, (ii) the greater interest of previous researchers in potential large-scale palaeovegetation changes, driven by glacial–interglacial climate cycles, and other significant periods of climatic change, such as the early-to-mid Holocene drought, (iii) the low sedimentation rate during the last millennia in certain regions, e.g. lowland Amazonia. Furthermore strong anthropogenic interference during the last 2 ka complicates the interpretation of many records from a palaeoclimate perspective. Additional difficulties arise from the one topic focus of many studies and authors do not often present the full range of data in their publications that are required for a 2 ka reconstruction.

### 5.2 Venezuelan Guayana highlands and uplands

In this region, highlands and uplands are discussed separately due to their outstanding disparities in physiographical, climatic and ecological features, as well as in the intensity of human pressure on their respective ecosystems.

Highlands are virtually pristine and, according to the paleoecological records, they have remained in this state at least since the early Holocene. Therefore, climate has been the main driver of change. Paleoecological records for the last 2 ka are scarce and generally of low resolution but a common trait is the ecological stability as expressed in the vegetation constancy. The following hypotheses have been suggested to explain these observations: (i) environmental changes were insufficient to affect the highland vegetation, (ii) the high precipitation and relative humidity of the Chimantá summits





CPD
11, 3475–3565, 2015

(Briceño et al., 1990) have buffered climatic changes, and (iii) the study sites are unsuitable for recording significant vegetation changes because there are no vegetation ecotones nearby (Rull, 2015). Further work is needed focused on these proposals. So far, paleoecological fieldwork atop the tepuis has been carried out in an exploratory, non-systematic manner due to the remoteness of the tepuis, and the logistic and administrative constraints (Rull et al., 2008). In the LOTRED-SA framework, the issue of vegetation constancy emerges as a priority and should be addressed properly by finding suitable coring sites to be analysed with high-resolution multiproxy tools. The use of physical-chemical proxies independent from pollen and spores is essential to record climatic shifts, thus avoiding circularity. Lake sediments would be excellent for this purpose but, unfortunately, lakes are absent on tepui summits, the only permanent lake known so far is lake Gladys atop the Roraima tepui, of which age and origin remain unknown (Safont et al., 2014). At present, the analysis of the `Apakará PATAM9-A07` core, which meet the PAGES-2 k criteria, is in progress. The preliminary study of this core showed the main Holocene vegetation trends at millennial resolution (Rull et al., 2011), and the current analysis is being performed at multidecadal resolution. A new core obtained in the Uei summit (PATAM8-A07; not included in the Chimantá massif) containing a decadal record for the last 2 ka is also being currently analysed (V. Rull, personal communication, 2015).

In the GS uplands, the situation is very different and the main driver of ecological change is fire. This does not mean that eventual climatic shifts have been absent or that they have not affected the vegetation but the action of anthropogenic fires overwhelms and obscures the action of climate (Montoya and Rull, 2011). So far, regional paleoclimatic trends based on the Cariaco records have been used as a reference for the GS uplands (Rull et al., 2013) but a more local paleoclimatic record for this area is still lacking and urgently needed, not only for the last 2 ka but also for the entire Holocene. Another limitation is that most paleoecological records available for the GS uplands are from its southern sector, which is the lowermost part of the peneplains, and has a different climate and vegetation regime as compared to the northern sec-





CPD
11, 3475–3565, 2015

tor. Some records from the northern sector are available that fit with the chronological PAGES-2 k requirements (Leal et al., 2011) but only summary diagrams are provided in peer-review publications and cannot be used in this reconstruction. The decadal to multidecadal analysis of a new core obtained in Kamoirán (PATAM10-A07), in the northern GS uplands, is in progress (V. Rull, personal communication, 2015).

It should be stressed that the last 2 ka seem to have been critical for the ecological history of the GS uplands and its detailed knowledge may be crucial to understand the origin of the present-day landscape. The reason is intimately linked to the temporal patterns of human impact using fire. The date of arrival of the current indigenous culture (Pemón) at GS is still unknown. Based mainly on historical documents, it has been postulated that this culture settled in GS ∼ 0.6 to 0.3 ka, coming from Guyana or Brazil (Thomas, 1982; Colson, 1985; Huber, 1995a). But these could be considered minimal ages, as recent palaeoecological studies suggest that human groups with landscape management practices similar to the Pemón people would have been present in the GS since ∼ 2 ka (Montoya and Rull, 2011; Montoya et al., 2011a). Before that time, the GS landscape was different from the present, including larger extents of forested areas since the Lateglacial and the absence of *Mauritia* palm swamps until ∼ 2 ka. The same time period seems to have been a landmark in neotropical history for similar reasons as Rull and Montoya (2014) showed a generalized increase of *Mauritia* pollen abundances in northern South America during the last 2 ka.

Given the northern position of the area, the vegetation responses studied have been normally related to ENSO and ITCZ movements and their consequences in the ocean–atmosphere circulation patterns. These two main drivers are included in Niño 3.4, AMO, IPO and TNA modes, which are those acting in the area as shown in the Figs. 2–5 (especially regarding temperature). Previously the effect of SAM has hardly been considered and the lack of AMO in the region regarding precipitation is surprising. It is noteworthy to compare the climatic inferences made through fossil pollen records and the climate modes effect on the area. Fossil pollen records have suggested available moisture (or precipitation/evapotranspiration ratio: P/E) as the main climatic driver to take into account for vegetation responses. However, these inferences are based on very local spatial scale proxies (e.g. algal remains) and P/E is a complex process that relies in a wide range of factors, including both temperature and precipitation. Its interpretation in the fossil record is therefore complex and sometimes ambiguous. On the other hand, climate modes have showed the potential large effect of both temperature and precipitation trends in the region. Such findings suggest that the variations of P/E inferred from the fossil record could be caused by either of these two factors, or by both. Additional higher resolution multi-proxy analyses should shed a light on previous undetected modes in the region as well as disentangling the combined effect of several forcing factors. Nevertheless, upland records have been interpreted as primarily human-driven vegetation responses, so for the last 2 ka the climatic conclusions are constrained. Highland records have been described as an example of constancy, even insensitive to temperature change during the last 2 ka, which could confirm that the temperature driven modes in this region have been of a lesser magnitude than those required to cross the vegetation tolerance ranges or the intrinsic characteristics of the sites studied so far inhibit detecting any change.

### 5.3 Northern Andes

Pristine regions have been not identified with certainty within this region, inhibiting a clear signal of climate tendencies in the last 2 ka. Drier conditions prevailed in Colombian savanna lowlands although the increased presence of *Mauritia* suggests either increased humidity or human influence. Along the Pacific coast, general wetter conditions prevailed (Fig. 8b) but tectonic events might be unsettling clear patterns. Interpretation of the records should be made with care due to the nosiness of the data. Furthermore, due to the geomorphological complexity of the landscape and its latitudinal characteristics, this region is prone to a combination of strong overlapping climate signals within and between years (Figs. 2–5; Marchant et al., 2001). The `Papallacacta` highlights the two modes of precipitation variability that interplay in this region, namely the eastern equatorial Pacific SST and the Atlantic SST, showed dominant climate forcing in





CPD
11, 3475–3565, 2015

the N Andes until 0.45 ka and interdecadal variability during the last 0.5 ka, respectively. Also Pallcacocha in S Ecuador shows a close match with ENSO recording its strength during the last 15 ka. Similarly associated with ENSO are the changes in the plant assemblages detected in the high resolution record of El Junco on the Galápagos islands.

Comparing vegetation-climate signals between the Colombian lowlands and E Venezuela and NE Brazil has shown opposite climate conditions. Dry conditions identified in the Colombian savannas (suggesting an ENSO – La Niña), concur with similar conditions in the Bolivian pollen records. During an El Niño setting, when Bolivian savannas indicated wet conditions, the signal from Lake Valencia in Venezuela reflected dry conditions (Wille et al., 2003). Lowland sites generally show similar patterns of climate change during the last 2 ka and apparent synchronous events are observed over a larger spatial scale. The sites in the Andean region are much more influenced by local geographical variability, causing a more variable response mechanism.

## 5.4 Central Andes

The records of the Altiplano suggest an oscillation in moisture availability (precipitation) on a multi-centennial timescale during the last 2 ka (Fig. 9). These oscillations are probably due to the strength of the summer precipitation. The timing of wet and dry events is not uniform between sites probably due to local micro-climates and differences in vegetation sensitivity to climate change (the high elevation grassland (Puna) vs. mid elevation Andean forest). The archaeological site of Cerro Llamoca provides the most robustly dated record (33 radiocarbon ages); however, the strong local human influence means that climatic interpretations of palaecological evidence should be done with caution. Records of glacial advance and retreat from the Altiplano record variations associated with the LIA, but in all records, apart from Llamoca, any climatic impact of the LIA on vegetation is masked by the European conquest effects (abandonment of the sites, and/or changes in agricultural practices).





CPD
11, 3475–3565, 2015

Interpretation of the climate signal from the C Andes fossil pollen records suggests that during the last 2 ka precipitation, rather than temperature, was the key natural driver of vegetation change. However, modelling suggests that on an annual scale temperature (Figs. 2 and 3), rather than precipitation (Figs. 4 and 5) is more likely to have altered due to switch in climate mode; particularly in the western part of the C Andes. The increase in temperature observed at `Coropuna` during the Inca period, after 0.85 ka, could correspond to El Niño or IPO forcing and the decrease in temperature observed at Marcacocha between 1.85 and 0.85 ka could be related to La Niña. Similarly these modes, show a high influence on the coast which is in agreement with the results of the coastal pollen record (`Urpi Cocha`) where ENSO is considered responsible for extreme flooding events. Also the TSA mode shows a strong influence on the Bolivian Altiplano. The greater sensitivity to precipitation seen in the pollen records is probably because moisture availability is in most areas the limiting factor for both vegetation communities and human populations. The increase of temperature induced by Niño and IPO on the Figures 2 and 3 show no link with the precipitation. On the Altiplano variation in the SASM has been attributed as a major driver of changes in moisture balance at `Llamoca, Coropuna`, `Pacucha`, `Consuelo` through altering the summer precipitation. Precipitation patterns (Figs. 4 and 5) are less pronounced as it occurs here during a short seasonal period of 2–3 months, hence the used month average weakens the correlation. Notwithstanding, ENSO has been shown to have significant influence in the region (both temperature and precipitation) in numerous studies.

### 5.4.1 Lowland Amazon Basin

Figures 2–5 reinforce the importance of the SAM in Amazonia, a pattern that has been identified and discussed extensively in the palaeoecology literature of lowland Amazonia. The SAM is recognised as a key driver of precipitation and attributed to the expansion of rainforest during the late Holocene, which is observed in the large lake records from S Amazonia (`Chaplin`, `Bella Vista`, `Orícore`, `Carajás`). However, these sites do not meet the PAGES-2 k dating criteria. As for its effect on tempera-





CPD
11, 3475–3565, 2015

ture, in this region vegetation records are probably not sensitive to small temperature changes (e.g. 0.5 °C) that might relate to SAM strength. The sensitivity of the records could be related to the temperature and precipitation ranges of tropical plant families (Punyasena, 2008; Punyasena et al., 2008). Figures 2–5 also show considerable spatial complexity in climate over lowland Amazonia, in terms of the impact of different climate modes, especially ENSO. However, if modes such as ENSO do have a long term drying effect over the past 2 ka in lowland Amazonia, it does not appear to affect vegetation in a way that is visible in the pollen records that we have reviewed. Given the size of the region and the relative sparseness of sites, it is perhaps unlikely that such spatial complexity would be captured.

The better-resolved late Holocene records tend to come from small lake basins (e.g. oxbows), which have small pollen catchment areas. This means that they reflect predominantly local-scale changes and are, therefore, more susceptible to having their palaeo-record dominated by signals of ancient human land use and local hydrology (e.g. savanna gallery forest), rather than regional climate. Many of these smaller records were specifically selected in the original study to investigate local-scale human impacts around known occupation records (Iriarte et al., 2012; Whitney et al., 2014; Carson et al., 2014, 2015).

In order to address these complicating factors of pollen catchment area and the anthropogenic signal, any future effort to obtain better-resolved Holocene pollen records in the lowland Amazon should make careful consideration of the sampling methodology employed. Carson et al. (2014) demonstrated that sampling a combination of small and large lake basins from within the same catchment allows a distinction to be made between local-scale, anthropogenic impact and regional-scale, climate-induced vegetation changes. In regions such as the C Amazon, where lakes are predominantly limited to small oxbows, an sampling approach might be to analyse cores from multiple records within the same locality, and to compare those records, in order to identify any regionally significant pattern of palaeovegetation change (Cohen et al., 2012; Whitney et al., 2014). Oxbow lakes are dynamic features, and so require careful interpretation.





CPD
11, 3475–3565, 2015

However, their higher sedimentation rate means that they have the potential to provide the high temporal resolution palaeovegetation records of the late Holocene, which currently are largely absent from the Amazon lowlands.

Considering the large area of the Amazon Basin, the number of pollen records is very small, and by applying the PAGES-2 k criteria, those numbers are further reduced. Furthermore, the records which are excluded from the analysis by these criteria include some of the most important records of climate-driven vegetation change in the Amazon basin, e.g. `Lakes Orícore` (Carson et al., 2014), `Carajás` (Hermanowski et al., 2012), and lakes `Bella Vista` and `Chaplin` (Mayle et al., 2000).

In order to avoid a "black hole" situation over the Amazon lowlands in any regional synthesis, one approach may be to apply a lower threshold of dating criteria. If the selection criteria are relaxed to allow for those records that are > 500 years old and have at least two chronological control points within the last 2000 years, a further 14 records are added to the list of qualifying records. Also, if the criteria are stretched further to allow records with a lower date which is older than, but close to 2 ka, the `Lake Chaplin` and `Gentry` records would also be included. Including these records would provide coverage from the central Amazon river region, the N Brazilian Amazon, the E and NE coastal Amazon and the SE and SW basin. However, even with these relaxed criteria, a number of key records would still be excluded, e.g. `Pata` (Bush et al., 2004; D'Apolito et al., 2013), `La Gaiba` (Whitney et al., 2011) and `Bella Vista` (Mayle et al., 2000).

Any future investigation of late-Holocene climate–vegetation interaction may require new dating efforts to improve the age models of these key records. A Holocene aged record from Laguna `La Gaiba` produced by McGlue et al. (2012) has produced a better-resolved age model than the longer record from Whitney et al. (2011), which would meet the PAGES-2 k criteria. However, McGlue et al. (2012) analysed the geochemical properties of sediments from a new core taken after the Whitney et al., (2011) study, and did not include any pollen data. No attempt has been made subsequently to correlate the chronologies of the two records.





CPD
11, 3475–3565, 2015

Although the dating resolution in the late Holocene is poor in many lowland Amazonian pollen records, it should be noted that the majority also show little variation in vegetation over the past ∼ 1 or 2 ka. Whether this reflects genuine ecosystem (and climate) stability over the late Holocene, or is a product of low sampling resolution within these long records is unclear. Most of these deep temporal pollen records, as they are published now, likely have sub-sample intervals of insufficient resolution to be able to discern high-frequency events, such as vegetation changes associated with ENSO variability. However, in some cases, such as `Bella Vista` and `Orícore`, the potential for such fine temporal reconstructions may be limited by the low sedimentation rate of the basins. Often these records come from short sediment cores, in which the Holocene time interval is contained within a short depth range (i.e. < 1 m). A number of shorter records, spanning Holocene time periods, exist in the eastern coastal Amazon, and could potentially provide high temporal-resolution reconstruction over the last 2 k. However, most do not currently meet the PAGES-2 k dating criteria.

## 5.5 Southern and southeastern Brazil

The limited number of pollen records from S/SE Brazil for LOTRED-SA-2 k has several reasons besides the insufficiently dated cores: (1) many archives, in particular peat bogs have a very low sedimentation rates. Often 100 cm of peat deposits cover already the complete Holocene and the last 2000 years have relative small amount of deposits, (2) the upper part of peat archives actively growing roots and it is difficult to date.

However, general vegetation changes in S/SE Brazil can be explained by a change to wetter conditions, in particular due the reduction of the dry season length. This is generally reflected in SE Brazil between 6 to 4 ka, and in particular strong in S/SE Brazil during the ∼ 1 ka. Several new records for S/SE Brazil are in process or to be studied in the next years. These records will most likely present improved chronology for the last 2 ka. Additional studies on this period are considered relevant for regional vegetation conservation and management plans (Behling and Pillar, 2007). The climate modes





CPD
11, 3475–3565, 2015

of the continent display a relatively simple pattern within this region as the degree of overlap is minimal.

### 5.6 Pampa plains

There are several pollen records in Pampa plains that span Holocene times, but few of them have well resolved chronologies for the last 2 ka. Just one site fulfils all PAGES-2 k criteria. Conventionally, pollen analyses in the region were carried out in alluvial sequences or archaeological sites which usually contain sedimentological discontinuities that impede a good chronological control. These pollen records show regional vegetation changes and climate inferences related to precipitation changes (humid/dry/arid conditions) or sea level fluctuations, mainly at millennial or centennial scale. Until today, few studies has been focused on elucidating palaeoenvironmental changes at high temporal resolution during the last 2 ka. Furthermore, the Pampa plains has a high number of potential sites; shallow lakes characterized by a continuous sedimentation that would provide robust age models and high quality pollen records. Conversely, the current pollen records do not have the necessary resolution to identify vegetation-human interaction during the last 0.3 ka and therefore improved chronological control higher resolution is necessary.

General climatic tendencies in the region can be inferred although the few accurate pollen records are available. While individual palaeoecological studies reveal local developments, general patterns emerge when information from several sites is combined together, such as `Lonkoy` and `Hinojales-San Leoncio` (Fig. 12b). A multiproxy approach, including pollen analyses, shows synchronic changes in these shallow lakes from SE Pampa that are mainly a response to precipitation variations. Thus, between 2 and 0.5 ka drier conditions than present are inferred, then a transition phase towards more humid conditions is observed which stabilizes between ∼ 0.3 and 0.1 ka, with values close to modern (Stutz et al., 2015). These climatic inferences are valid for the SE region but do not extend to the entire Pampa plains. At S Pampa plains, multiproxy interpretation at Sauce Grande shows a similar change to more humid conditions





CPD
11, 3475–3565, 2015

at 0.66 ka, and similar conditions to present day after 0.27 ka, but pollen composition shows low responsiveness to change (Fig. 12a). As seen in Figs. 2–5, these plains falls outside the areas influenced by strong climate modes expressions. New paleoenvironmental reconstructions based on pollen records are needed to disentangle the intrinsic ecosystem variability from climate, and to elucidate if climatic events as MCA or LIA had different expressions in the Pampa region.

### 5.7 Southern Andes and Patagonia

Even though a high number of pollen records are available in the region, just 19 (between 32–54° S) fulfil the PAGES-2 k criteria. In Patagonia most of pollen studies have been carried out on long temporal records (in many cases until end of Last Glacial Maximum) focusing on the Pleistocene–Holocene transition or the entire Holocene vegetation and climate dynamics. Moreover, appropriate records in areas of northern S Andes and Patagonia, are scarce because of the absence of depositional sites and archives or the lack of palaeo-research.

The pollen records are considered to mainly reflect the SWWB. Southern records receive precipitation related to the SWWB, whereas those located to the north (40–32° S) are also influenced by the Subtropical Pacific Anticyclone (SPA) that blocks winter precipitation in a latitudinal gradient (decreasing precipitation during JJA in the S part to scarce precipitation during DJF in the N part). Those sites located in the Patagonia receive extreme precipitation events from east. Superimposed to SWWB and SPA dynamics are Southern Annular Mode/Antarctic Oscillation (SAM) and ENSO (Figs. 2–5). Thus, the comparison between N and S records could shed light on expansion/retraction and/or latitudinal shifts of the SWWB, or differential influence of SPA. For example, records S of 46° S show relatively dry conditions between ∼ 1–0.5 ka whereas drought occurs between 2–1.5 ka at sites N of this latitude. Records N of 41° S show more climatic variability. Differences in seasonality is a key feature of precipitation records between N Patagonia (summer rainfall, e.g. `Lago San Pedro`) and central Chile (winter rainfall, e.g. `Lago Aculeo` and `Palo Colorado`). Furthermore,





CPD
11, 3475–3565, 2015

southernmost Patagonia arises as a key area to study climate–vegetation variability associated to SAM (e.g. `Lago Cipreces`). Sites in N Patagonia and C Chile reflect synchronicity with ENSO activity (e.g. `Lagos San Pedro` and `Aculeo`) given the relationship between high precipitation/El Niño phase and low precipitation/La Niña phase (Montecinos and Aceituno, 2003). LIA and MCA chronozones are well recorded both in southern and northern Patagonia (e.g. `Lagos Cipreses`, `Peninsula Avellaneda Bajo`, `San Pedro`), however not in central Chile. The region cannot be explained by a single climate unit due to the presence of different climatic modes and forcing. Different patterns are distinguished (Fig. 13b), due to their geographical position, latitude and E/W side of the Andes, and intrinsic sensitivity of each record to climatic variability. For example, wet conditions are inferred in N Patagonia between ∼ 1.5–0.3 ka whilst in S Patagonia dry conditions dominated with increased variability.

## 6 Synthesis and conclusions

Although the number of pollen records suitable for a 2 ka climate reconstruction is still relatively small compared to the total potential number of records available from South America (Flantua et al., 2015a), an increasing number of records are showing potential for inclusion in PAGES-2 k. From reviewing c. 180 pollen records from South America we conclude that:

– the lack of South American records that fulfil PAGES-2 k criteria is an issue of short vs. long records. Most of the more important records have been ruled out because they turned out to be "old" and based on the sedimentation rates of the sedimentary archives, radiocarbon samples within the last two millennia are mostly missing.

– Pollen records detect long-distance synchronicity (differences and similarities) in vegetation changes as an indication of regional precipitation and temperature variability, but they also detect the local-scale change/variability. Diverse patterns of





CPD
11, 3475–3565, 2015

vegetation response to climate change are observed, with more similar patterns of change in the lowlands and varying intensity and direction of responses in the highlands. Hence pollen records can serve as integrating proxies over long distances and allow assessing changes in the large-scale atmospheric circulation. Therefore they can serve as powerful archives, which can help better understand past changes in the strength and area of influence of climate modes such as ENSO or the AMO.

- Throughout South America a number of overlapping climate modes operate, meaning that every single pollen record most likely captures the signal of various modes (Figs. 2–5), although they do not all operate in the same frequency bands and modes interact with one another through constructive interference. The causes of ambiguous climate–vegetation responses observed in pollen records can therefor probably be best ascribed to the degree of climate mode interaction at a location.

- Depending on the geographical and altitudinal location a record may be more sensitive to temperature- or precipitation- related forcing (Figs. 7–13). The baseline for understanding climate- driven changes in vegetation is related to either of these variables, but interpreting pollen records in terms of a response to large-scale climatic forcing may yield further insights as it allows for an attribution of, temperature- and/precipitation- driven changes to forcing from climate modes originating in either from Atlantic or Pacific.

- For human impact studies, it is important to consider a set of different proxies to make more confident interpretations in terms of climate vs. human drivers of vegetation changes.

- There is a need to increase efforts in high- resolution studies with accurate chronology for the last 2 ka.





CPD
11, 3475–3565, 2015

– The PAGES-2 k criteria should be adjusted for pollen records, especially by applying a lower threshold of dating criteria. A region such as the lowland Amazon is notorious known for its paucity of records with good dating (e.g. Ledru et al., 1998). Therefore the few valuable sites available should be considered for the overall purpose of understanding vegetation-climate linkages.

## 7 Recommendations

Below we list a few specific recommendations for future engagements between climate and pollen related studies:

1. quantitative translation from pollen metrics to climate variables: assembling a meaningful multi-site and multi-proxy dataset is hampered by the current gap between the palynological and the climate dynamics and modelling community, both in terms of interpretation and quantitative translation of pollen data into climate indicators. This gap can be narrowed when pollen studies provide – if the data is suitable for that purpose – their own temperature or precipitation approximations. There are only a few pollen studies that provide a quantitative interpretation of their pollen data in terms of a climate variable. In the Andes, `La Cocha-1` (González et al., 2012) and `Papallacta PA1-08` (Ledru et al., 2013) provide such estimates of climatological changes. In both cases the percentage of arboreal pollen was used as a measurement of moisture or temperature changes. Similarly Punyasena et al. (2008) and Whitney et al. (2011) present innovative methodologies for climate reconstructions in the lowland tropics, and Markgraf et al. (2002), Tonello and Prieto (2008) Tonello et al. (2009, 2010) and Schäbitz et al. (2013) in this southern SA. Providing additional climate estimates is not common feature in palynological studies and this missing link becomes more obvious when the palynology community is being engaged into a multi-disciplinary effort such as LOTRED-SA and PAGES-2 k.





CPD
11, 3475–3565, 2015

2. Multi-proxy based research should become a mandatory goal for all further investigations. Caution should be exercised when interpreting apparently contradictory records provided by different groups for the same region; the interpretation of climatic and anthropogenic signals in each record may be based on very different (indirect) proxies. Hence the apparent asynchronies or contradictory interpretations could simply occur as a result of methodological artefacts (e.g. by not including charcoal records, non-pollen palynomorphs, geochemical analyses, etc.). On the other hand, this is especially relevant for those areas where human impact has been found for the last 2 ka and any climatic interpretation is aimed.

3. For the stated purposes of the current and future PAGES initiatives, researchers should be motivated to further improve chronologies for existing sites. Further advances in understanding climate–human relationships are also likely to be made by the integration of palaeoecological and archaeological data (e.g. Mayle and Iriarte (2014) through conceptual modelling, which can provide a framework for identifying patterns and trajectories of change (e.g. Gosling and Williams, 2013).

4. Multi-proxy studies should compare data between different regions and records (but comparable in terms of chronology and resolution) as it may yield insight into anti-phased climate variability resulting from certain dominant climate modes, (e.g. a comparison between the coast of Colombia and NE Brazil–Guianas vs. Brazil and E Argentina.).

5. All Andean zones are quite active from tectonic and volcanic points of view, and those drivers will have had huge impacts on the vegetation and maybe in the fossil pollen records signal. However, this feature has been only included in the southern region of Andes. A chronology database focused on tephra control points could support current chronology constraints and improve comparison between records. The recent geochronological database of the LAPD can support multi-proxy approach for paleoecological integration (Flantua et al., 2015b).





CPD
11, 3475–3565, 2015

6. In this paper we focused less on the seasonal contrasts throughout the continent, but in southern SA the seasonal component is extremely important, as the latitudinal gradient heavily influences the rainfall pattern throughout the continent. Precipitation in this region is the limiting factor for the growth and production of pollen. Key questions that need further study include (a) a better understanding of the relationship between winter and summer rainfall, (b) if this relationship has remained stationary over the last 2 ka, (c) if changes in the intensity or location (latitudinal shift) of rainfall have occurred.

**The Supplement related to this article is available online at doi:10.5194/cpd-11-3475-2015-supplement.**

*Author contributions.* S. G. A. Flantua, C. González-Arango, H. Hooghiemstra conceived the paper and H. Hooghiemstra supervised the project. M. Vuille developed the climate modes and corresponding figures, I. Hoyos supported the interpretation of the climate settings of the N and C Andes; H. Behling the S and SE Brazil sections; J. F. Carson, F. Mayle, B. S. Whitney the lowland Amazon sections; W. D. Gosling, M. P. Ledru the C Andes sections; S. G. A. Flantua, V. Rull, H. Hooghiemstra the N Andes sections; A. Maldonado and M. S. Tonello the Patagonia and S Andes sections; M. S. Tonello the Pampa sections; C. González-Arango and S. G. A. Flantua provided the initial drafts of the climate summary figures and all authors discussed the results and implications; S. G. A. Flantua, C. González-Arango, M. Vuille, B. S. Whitney, J. F. Carson, H. Hooghiemstra structured and edited the manuscript. All authors commented on the manuscript at all stages.

*Acknowledgements.* We thank the Netherlands Organization for Scientific Research (NWO, grant 2012/13248/ALW) for financial support to the project of Suzette Flantua. We are grateful for the support provided to Mathias Vuille by NSF-P2C2 (AGS-1303828) and to Encarni Montoya by the NERC fellowship (NE/J018562/1). For the setup of the LAPD, we would like to thank the Amsterdam-based Hugo-de-Vries-Foundation for supporting this work between 2009 and 2012 by three grants. We are very grateful to Martin Grosjean, Ricardo Villalba, José Ignácio Martinez, Catalina Gonzalez and Thorsten Kiefer for organizing the LOTRED-SA





CPD
11, 3475–3565, 2015

Special Issue "Climate change and human impact in Central and South America over the last 2000 years: observations and Models" and for allowing us submit our work to this CPD Special Issue (http://www.clim-past-discuss.net/special_issue88.html).

## References


Andreoli, R. V. and Kayano, M. T.: ENSO-related rainfall anomalies in South America and associated circulation features during warm and cold Pacific decadal oscillation regimes, Int. J. Climatol., 25, 2017–2030, doi:10.1002/joc.1222, 2005.

Bakker, J., Moscol Olivera, M., and Hooghiemstra, H.: Holocene environmental change at the upper forest line in northern Ecuador, Holocene, 18, 877–893, doi:10.1177/0959683608093525, 2008.

Behling, H.: A high resolution Holocene pollen record from Lago do Pires, SE Brazil: vegetation, climate and fire history, J. Paleolimnol., 14, 253–268, 1995.

Behling, H.: Late glacial and Holocene vegetation, climate and fire history inferred from Lagoa Nova in the southeastern Brazilian lowland, Veg. Hist. Archaeobot., 12, 263–270, doi:10.1007/s00334-003-0020-9, 2003.

Behling, H. and Da Costa, M. L.: Holocene environmental changes from the Rio Curuá record in the Caxiuanã region, eastern Amazon Basin, Quaternary Res., 53, 369–377, doi:10.1006/qres.1999.2117, 2000.

Behling, H. and Da Costa, M. L.: Holocene vegetational and coastal environmental changes from the Lago Crispim record in northeastern Pará State, eastern Amazonia, Rev. Palaeobot. Palyno., 114, 145–155, 2001.

Behling, H. and Hooghiemstra, H.: Holocene Amazon rainforest-savanna dynamics and climatic implications: high-resolution pollen record from Laguna Loma Linda in eastern Colombia, J. Quaternary Sci., 15, 687–695, 2000.

Behling, H. and Safford, H. D.: Late-glacial and Holocene vegetation, climate and fire dynamics in the Serra dos Órgãos, Rio de Janeiro State, southeastern Brazil: late Quaternary environmental dynamics, Glob. Change Biol., 16, 1661–1671, doi:10.1111/j.1365-2486.2009.02029.x, 2010.

Behling, H. and Pillar, V. D.: Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of




CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

modern Araucaria forest and grassland ecosystems, Philos. T. Roy. Soc. B, 362, 243–251, doi:10.1098/rstb.2006.1984, 2007.

Behling, H., Hooghiemstra, H., and Negret, A.: Holocene history of the Chocó rain forest from Laguna Piusbi, southern Pacific lowlands of Colombia, Quaternary Res., 50, 300–308, 1998a.

Behling, H., Negret, A. J., and Hooghiemstra, H.: Late Quaternary vegetational and climatic change in the Popayán region, southern Colombian Andes, J. Quaternary Sci., 13, 43–53, 1998b.

Behling, H., Pillar, V. D., and Bauermann, S. G.: Late Quaternary grassland (Campos), gallery forest, fire and climate dynamics, studied by pollen, charcoal and multivariate analysis of the São Francisco de Assis core in western Rio Grande do Sul (southern Brazil), Rev. Palaeobot. Palyno., 133, 235–248, doi:10.1016/j.revpalbo.2004.10.004, 2005.

Behling, H., Pillar, V. D., Müller, S. C., and Overbeck, G. E.: Late-Holocene fire history in a forest-grassland mosaic in southern Brasil: implications for conservation, Appl. Veg. Sci., 10, 81–90, 2007.

Bellwood, P.: First Farmers: The Origins of Agricultural Societies, Wiley, Malden, 2004.

Berrio, J. C., Hooghiemstra, H., Behling, H., and Van der Borg, K.: Late Holocene history of savanna gallery forest from Carimagua area, Colombia, Rev. Palaeobot. Palyno., 111, 295–308, 2000.

Berrio, J. C., Hooghiemstra, H., Behling, H., Botero, P., and Van der Borg, K.: Late-Quaternary savanna history of the Colombian Llanos Orientales from Lagunas Chenevo and Mozambique: a transect synthesis, Holocene, 12, 35–48, doi:10.1191/0959683602hl518rp, 2002.

Berry, P. E., Huber, O., and Holst, B. K.: Floristic analysis and phytogeography, in: Flora of the Venezuelan Guayana, vol. 1. Introduction, edited by: Berry, P. E., Holst, B. K., and Yatskievych, K., Missouri Botanical Garden Press, St. Louis, 161–191, 1995.

Boninsegna, J. A., Argollo, J., Aravena, J. C., Barichivich, J., Christie, D., Ferrero, M. E., Lara, A., Le Quesne, C., Luckman, B. H., Masiokas, M., Morales, M., Oliveira, J. M., Roig, F., Srur, A., and Villalba, R.: Dendroclimatological reconstructions in South America: a review, Palaeogeogr. Palaeocl., 281, 210–228, doi:10.1016/j.palaeo.2009.07.020, 2009.

Branch, N. P., Kemp, R. A., Silva, B., Meddens, F. M., Williams, A., Kendall, A., and Pomacanchari, C. V.: Testing the sustainability and sensitivity to climatic change of terrace agricultural systems in the Peruvian Andes: a pilot study, J. Archaeol. Sci., 34, 1–9, doi:10.1016/j.jas.2006.03.011, 2007.





CPD
11, 3475–3565, 2015

Briceño, H., Schubert, C., and Paolini, J.: Table-mountain geology and surficial geochemistry: Chimantá Massif, Venezuelan Guayana shield, J. S. Am. Earth Sci., 3, 179–194, doi:10.1016/0895-9811(90)90002-I, 1990.
Burbridge, R. E., Mayle, F. E., and Killeen, T. J.: Fifty-thousand-year vegetation and climate history of Noel Kempff Mercado National Park, Bolivian Amazon, Quaternary Res., 61, 215–230, doi:10.1016/j.yqres.2003.12.004, 2004.
Bush, M. B. and Rivera, R.: Reproductive ecology and pollen representation among neotropical trees, Global Ecol. Biogeogr., 10, 359–367, 2001.
Bush, M. B., De Oliveira, P. E., Colinvaux, P. A., Miller, M. C., and Moreno, J. E.: Amazonian paleoecological histories: one hill, three watersheds, Palaeogeogr. Palaeocl., 214, 359–393, doi:10.1016/j.palaeo.2004.07.031, 2004.
Bush, M. B., Silman, M. R., and Listopad, C. M. C. S.: A regional study of Holocene climate change and human occupation in Peruvian Amazonia: Amazonian climate change and settlement, J. Biogeogr., 34, 1342–1356, doi:10.1111/j.1365-2699.2007.01704.x, 2007a.
Bush, M. B., Silman, M. R., de Toledo, M. B., Listopad, C., Gosling, W. D., Williams, C., de Oliveira, P. E., and Krisel, C.: Holocene fire and occupation in Amazonia: records from two lake districts, Philos. T. Roy. Soc. B, 362, 209–218, doi:10.1098/rstb.2006.1980, 2007b.
Carson, J. F., Whitney, B. S., Mayle, F. E., Iriarte, J., Prümers, H., Soto, J. D., and Watling, J.: Environmental impact of geometric earthwork construction in pre-Columbian Amazonia, P. Natl. Acad. Sci. USA, 111, 10497–10502, doi:10.1073/pnas.1321770111, 2014.
Carson, J. F., Watling, J., Mayle, F. E., Whitney, B. S., Iriarte, J., Prümers, H., and Soto, J. D.: Pre-Columbian land use in the ring-ditch region of the Bolivian Amazon, Holocene, doi:10.1177/0959683615581204, 2015.
Carvalho, L. M. V., Jones, C., and Ambrizzi, T.: Opposite phases of the Antarctic Oscillation and relationships with intraseasonal to interannual activity in the tropics during the Austral Summer, J. Climate, 18, 702–718, doi:10.1175/JCLI-3284.1, 2005.
Cheng, H., Sinha, A., Cruz, F. W., Wang, X., Edwards, R. L., d' Horta, F. M., Ribas, C. C., Vuille, M., Stott, L. D., and Auler, A. S.: Climate change patterns in Amazonia and biodiversity, Nature Communications, 4, 1411, doi:10.1038/ncomms2415, 2013.
Chepstow-Lusty, A.: Agro-pastoralism and social change in the Cuzco heartland of Peru: a brief history using environmental proxies, Antiquity, 85, 570–582, doi:10.1017/S0003598X0006796X, 2011.





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

Chepstow-Lusty, A. and Jonsson, P.: Inca agroforestry: lessons from the past, AMBIO, 29, 322–328, doi:10.1579/0044-7447-29.6.322, 2000.
Chepstow-Lusty, A. J., Bennett, K. D., Switsur, V. R., and Kendall, A.: 4000 years of human impact and vegetation change in the central Peruvian Andes – with events parallelling the Maya record?, Antiquity, 70, 824–833, 1996.
Chepstow-Lusty, A. J., Bennett, K. D., Fjeldsa, J., Kendall, A., Galiano, W., and Herrera, A. T.: Tracing 4,000 years of environmental history in the Cuzco area, Peru, from the pollen record, Mt. Res. Dev., 18, 159, doi:10.2307/3673971, 1998.
Chepstow-Lusty, A., Frogley, M. R., Bauer, B. S., Bush, M. B., and Herrera, A. T.: A late Holocene record of arid events from the Cuzco region, Peru, J. Quaternary Sci., 18, 491–502, doi:10.1002/jqs.770, 2003.
Cohen, M. C. L., Pessenda, L. C. R., Behling, H., de Fátima Rossetti, D., França, M. C., Guimarães, J. T. F., Friaes, Y., and Smith, C. B.: Holocene palaeoenvironmental history of the Amazonian mangrove belt, Quaternary Sci. Rev., 55, 50–58, doi:10.1016/j.quascirev.2012.08.019, 2012.
Colinvaux, P. A. and Schofield, E. K.: Historical ecology in the Galapagos Islands: I. A Holocene pollen record from El Junco Lake, Isla San Cristobal, J. Ecol., 64, 989, doi:10.2307/2258820, 1976.
Colson, A. B.: Routes of knowledge, an aspect of regional integration in the circum-Roraima area of the Guayana Highlands, Antropológica, 63/64, 103–149, 1985.
Curtis, S. and Hastenrath, S.: Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events, J. Geophys. Res.-Oceans, 100, 15835–15847, doi:10.1029/95JC01502, 1995.
D'Apolito, C., Absy, M. L., and Latrubesse, E. M.: The Hill of Six Lakes revisited: new data and re-evaluation of a key Pleistocene Amazon site, Quaternary Sci. Rev., 76, 140–155, doi:10.1016/j.quascirev.2013.07.013, 2013.
Da Silva Meneses, M. E. N., da Costa, M. L., and Behling, H.: Late Holocene vegetation and fire dynamics from a savanna–forest ecotone in Roraima State, northern Brazilian Amazon, J. S. Am. Earth Sci., 42, 17–26, doi:10.1016/j.jsames.2012.10.007, 2013.
de Porras, M. E., Maldonado, A., Abarzúa, A. M., Cárdenas, M. L., Francois, J. P., Martel-Cea, A., Stern, C. R., Méndez, C., and Reyes, O.: Postglacial vegetation, fire and climate dynamics at central Chilean Patagonia (Lake Shaman, 44° S), Quaternary Sci. Rev., 50, 71–85, 2012.





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

de Porras, M. E., Maldonado, A., Quintana, F. A., Martel-Cea, A., Reyes, O., and Méndez, C.: Environmental and climatic changes in central Chilean Patagonia since the Late Glacial (Mallín El Embudo, 44° S), Clim. Past, 10, 1063–1078, doi:10.5194/cp-10-1063-2014, 2014.
De Toledo, M. B. and Bush, M. B.: A mid-Holocene environmental change in Amazonian savannas: a mid-Holocene environmental change in Amazonian savannas, J. Biogeogr., 34, 1313–1326, doi:10.1111/j.1365-2699.2006.01606.x, 2007.
Dillehay, T. D., Eling, H. H., and Rossen, J.: Preceramic irrigation canals in the Peruvian Andes, P. Natl. Acad. Sci. USA, 102, 17241–17244, doi:10.1073/pnas.0508583102, 2005.
Doyle, M. E. and Barros, V. R.: Midsummer low-level circulation and precipitation in subtropical South America and related sea surface temperature anomalies in the South Atlantic, J. Climate, 15, 3394–3410, doi:10.1175/1520-0442(2002)015<3394:MLLCAP>2.0.CO;2, 2002.
Echeverria, M. E., Sottile, G. D., Mancini, M. V., and Fontana, S. L.: *Nothofagus* forest dynamics and palaeoenvironmental variations during the mid and late Holocene, in southwest Patagonia, Holocene, 24, 957–969, doi:10.1177/0959683614534742, 2014.
Enfield, D. B., Mestas-Nuñez, A. M., Mayer, D. A., and Cid-Serrano, L.: How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures?, J. Geophys. Res.-Oceans, 104, 7841–7848, doi:10.1029/1998JC900109, 1999.
Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J.: The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S., Geophys. Res. Lett., 28, 2077–2080, doi:10.1029/2000GL012745, 2001.
Espinoza Villar, J. C., Ronchail, J., Guyot, J. L., Cochonneau, G., Naziano, F., Lavado, W., De Oliveira, E., Pombosa, R., and Vauchel, P.: Spatio-temporal rainfall variability in the Amazon Basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador), Int. J. Climatol., 29, 1574–1594, doi:10.1002/joc.1791, 2009.
ESRI: ArcGIS, Redlands, CA, 2012.
Fjeldså, J. and Kessler, M.: Conserving the Biological Diversity of Polylepis Woodlands of the Highland of Peru and Bolivia. A Contribution to Sustainable Natural Resource Management in the Andes, NORDECO, Copenhagen, 1996.
Flantua, S. G. A., Hooghiemstra, H., Grimm, E. C., Behling, H., Bush, M. B., González-Arango, C., Gosling, W. D., Ledru, M. P., Lozano-García, S., Maldonado, A., Prieto, A. R., Rull, V., and Van Boxel, J. H.: Updated site compilation of the Latin American Pollen Database: challenging new research, Rev. Palaeobot. Palyno., in press, 2015a.





CPD
11, 3475–3565, 2015
Climate variability and human impact in South America during the last 2000 years
S. G. A. Flantua et al.

Flantua, S. G. A., Hooghiemstra, H., and Blaauw, M.: Quality assessment of chronologies in Latin American pollen records: a contribution to centennial to millennial scale studies of environmental change, Clim. Past Discuss., 11, 1219–1262, doi:10.5194/cpd-11-1219-2015, 2015b.
Fletcher, M.-S. and Moreno, P. I.: Vegetation, climate and fire regime changes in the Andean region of southern Chile (38° S) covaried with centennial-scale climate anomalies in the tropical Pacific over the last 1500 years, Quaternary Sci. Rev., 46, 46–56, doi:10.1016/j.quascirev.2012.04.016, 2012.
Folland, C. K., Renwick, J. A., Salinger, M. J., and Mullan, A. B.: Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone, Geophys. Res. Lett., 29, 21–1, doi:10.1029/2001GL014201, 2002.
Fontana, S. L.: Holocene vegetation history and palaeoenvironmental conditions on the temperate Atlantic coast of Argentina, as inferred from multi-proxy lacustrine records, J. Paleolimnol., 34, 445–469, doi:10.1007/s10933-005-5792-8, 2005.
Garralla, S. S.: Análisis polínico de una secuencia sedimentaria del Holoceno Tardío en el Abra del Infiernillo, Tucumán, Argentina, Polen, 12, 53–63, 2003.
Garreaud, R. and Battisti, D. S.: Interannual (ENSO) and interdecadal (ENSO-like) variability in the Southern Hemisphere Tropospheric Circulation*, J. Climate, 12, 2113–2123, doi:10.1175/1520-0442(1999)012<2113:IEAIEL>2.0.CO;2, 1999.
Garreaud, R., Lopez, P., Minvielle, M., and Rojas, M.: Large-scale control on the Patagonian climate, J. Climate, 26, 215–230, doi:10.1175/JCLI-D-12-00001.1, 2013.
Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J.: Present-day South American climate, Palaeogeogr. Palaeocl., 281, 180–195, doi:10.1016/j.palaeo.2007.10.032, 2009.
Ghersa, C. M. and León, R. J. C.: Ecología del paisaje Pampeano: consideraciones para su manejo y conservación, in: Ecología de Paisajes, edited by: Naveh, Z. and Lieberman, A. S., Editorial Facultad de Agronomía, Buenos Aires, 471–512, 2001.
Giannini, A., Chiang, J. C. H., Cane, M. A., Kushnir, Y., and Seager, R.: The ENSO teleconnection to the tropical Atlantic Ocean: contributions of the remote and local SSTs to rainfall variability in the tropical Americas*, J. Climate, 14, 4530–4544, doi:10.1175/1520-0442(2001)014<4530:TETTTT>2.0.CO;2, 2001.
Gillett, N. P., Kell, T. D., and Jones, P. D.: Regional climate impacts of the Southern Annular Mode, Geophys. Res. Lett., 33, L23704, doi:10.1029/2006GL027721, 2006.





CPD
11, 3475–3565, 2015

González-Carranza, Z., Hooghiemstra, H., and Vélez, M. I.: Major altitudinal shifts in Andean vegetation on the Amazonian flank show temporary loss of biota in the Holocene, Holocene, 22, 1227–1241, 2012.

Gosling, W. D. and Williams, J. J.: Ecosystem service provision sets the pace for pre-Hispanic societal development in the central Andes, Holocene, 23, 1619–1624, doi:10.1177/0959683613496296, 2013.

Grimm, A. M., Barros, V. R., and Doyle, M. E.: Climate variability in southern South America associated with El Niño and La Niña events, J. Climate, 13, 35–58, doi:10.1175/1520-0442(2000)013<0035:CVISSA>2.0.CO;2, 2000.

Groot, M. H. M., Hooghiemstra, H., Berrio, J. C., and Giraldo, C.: North Andean environmental and climatic change at orbital to submillennial time-scales: vegetation, water levels and sedimentary regimes from Lake Fúquene 130–27 ka, Rev. Palaeobot. Palyno., 197, 186–204, doi:10.1016/j.revpalbo.2013.04.005, 2013.

Gupta, A. S. and England, M. H.: Coupled ocean–atmosphere–ice response to variations in the Southern Annular Mode, J. Climate, 19, 4457–4486, doi:10.1175/JCLI3843.1, 2006.

Hastenrath, S. and Greischar, L.: Circulation mechanisms related to northeast Brazil rainfall anomalies, J. Geophys. Res.-Atmos., 98, 5093–5102, doi:10.1029/92JD02646, 1993.

Hermanowski, B., da Costa, M. L., and Behling, H.: Environmental changes in southeastern Amazonia during the last 25,000 yr revealed from a paleoecological record, Quaternary Res., 77, 138–148, doi:10.1016/j.yqres.2011.10.009, 2012.

Heusser, C. J.: Late quaternary forest-steppe contact zone, Isla Grande de Tierra del Fuego, subantarctic South America, Quaternary Sci. Rev., 12, 169–177, 1993.

Hillyer, R., Valencia, B. G., Bush, M. B., Silman, M. R., and Steinitz-Kannan, M.: A 24,700-yr paleolimnological history from the Peruvian Andes, Quaternary Res., 71, 71–82, doi:10.1016/j.yqres.2008.06.006, 2009.

Huber, O.: Recent advances in the phytogeography of the Guayana region, South America, Mém. Société Biogéographique, 3, 53–63, 1994.

Huber, O.: Geographical and physical features, in: Flora of the Venezuelan Guayana, vol. 1. Introduction, edited by: Berry, P. E., Holst, B. K., and Yatskievych, K., Missouri Botanical Garden Press, St. Louis, 1–62, 1995a.

Huber, O.: Vegetation, in: Flora of the Venezuelan Guayana, vol. 1. Introduction, edited by: Berry, P. E., Holst, B. K., and Yatskievych, K., Missouri Botanical Garden Press, St. Louis, 97–160, 1995b.





CPD

11, 3475–3565, 2015

Huber, O. and Febres, G.: Guía ecológica de la Gran Sabana, 1st edn., The Nature Conservancy, Caracas, Venezuela, 2000.
Huber, U. M. and Markgraf, V.: European impact on fire regimes and vegetation dynamics at the steppe-forest ecotone of southern Patagonia, Holocene, 13, 567–579, doi:10.1191/0959683603hl647rp, 2003.
Iglesias, V. and Whitlock, C.: Fire responses to postglacial climate change and human impact in northern Patagonia (41–43° S), P. Natl. Acad. Sci. USA, 111, E5545–5554, doi:10.1073/pnas.1410443111, 2014.
Iriarte, J., Power, M. J., Rostain, S., Mayle, F. E., Jones, H., Watling, J., Whitney, B. S., and McKey, D. B.: Fire-free land use in pre-1492 Amazonian savannas, P. Natl. Acad. Sci. USA, 109, 6473–6478, doi:10.1073/pnas.1201461109, 2012.
Jantz, N. and Behling, H.: A Holocene environmental record reflecting vegetation, climate, and fire variability at the Páramo of Quimsacocha, southwestern Ecuadorian Andes, Veg. Hist. Archaeobot., 21, 169–185, doi:10.1007/s00334-011-0327-x, 2012.
Jara, I. A. and Moreno, P. I.: Temperate rainforest response to climate change and disturbance agents in northwestern Patagonia (41° S) over the last 2600 years, Quaternary Res., 77, 235–244, doi:10.1016/j.yqres.2011.11.011, 2012.
Jara, I. A. and Moreno, P. I.: Climatic and disturbance influences on the temperate rainforests of northwestern Patagonia (40° S) since ∼ 14500 cal yr BP, Quaternary Sci. Rev., 90, 217–228, doi:10.1016/j.quascirev.2014.01.024, 2014.
Jeske-Pieruschka, V. and Behling, H.: Palaeoenvironmental history of the Sao Francisco de Paula region in southern Brazil during the late Quaternary inferred from the Rincao das Cabritas core, Holocene, 22, 1251–1262, doi:10.1177/0959683611414930, 2012.
Jeske-Pieruschka, V., Fidelis, A., Bergamin, R. S., Vélez, E., and Behling, H.: Araucaria forest dynamics in relation to fire frequency in southern Brazil based on fossil and modern pollen data, Rev. Palaeobot. Palyno., 160, 53–65, doi:10.1016/j.revpalbo.2010.01.005, 2010.
Jeske-Pieruschka, V., Pillar, V. D., De Oliveira, M. A. T., and Behling, H.: New insights into vegetation, climate and fire history of southern Brazil revealed by a 40,000 year environmental record from the State Park Serra do Tabuleiro, Veg. Hist. Archaeobot., 22, 299–314, doi:10.1007/s00334-012-0382-y, 2013.
Kuentz, A., de Mera, A. G., Ledru, M.-P., and Thouret, J.-C.: Phytogeographical data and modern pollen rain of the puna belt in southern Peru (Nevado Coropuna, western Cordillera), J. Biogeogr., 34, 1762–1776, doi:10.1111/j.1365-2699.2007.01728.x, 2007.





CPD
11, 3475–3565, 2015
Climate variability and human impact in South America during the last 2000 years
S. G. A. Flantua et al.

Kuentz, A., Ledru, M.-P., and Thouret, J.-C.: Environmental changes in the highlands of the western Andean Cordillera, southern Peru, during the Holocene, Holocene, 22, 1215–1226, doi:10.1177/0959683611409772, 2012.

Leal, A., Perez, T., and Bilbao, B.: Contribution to Early Holocene vegetation and climate history of Eastern Orinoco Llanos, Venezuela, from a paleoecological record of a Mauritia Lf swamp, Acta Amaz., 41, 513–520, 2011.

Ledru, M. P., Bertraux, J., and Sifeddine, A.: Absence of Last Glacial Maximum records, Quaternary Res., 49, 233–237, 1998.

Ledru, M.-P., Jomelli, V., Bremond, L., Ortuño, T., Cruz, P., Bentaleb, I., Sylvestre, F., Kuentz, A., Beck, S., Martin, C., Paillès, C., and Subitani, S.: Evidence of moist niches in the Bolivian Andes during the mid-Holocene arid period, Holocene, 23, 1547–1559, doi:10.1177/0959683613496288, 2013.

Legates, D. R. and Willmott, C. J.: Mean seasonal and spatial variability in gauge-corrected, global precipitation, Int. J. Climatol., 10, 111–127, doi:10.1002/joc.3370100202, 1990.

Lewis, S. L., Brando, P. M., Phillips, O. L., Van der Heijden, G. M. F., and Nepstad, D.: The 2010 Amazon drought, Science, 331, 554–554, doi:10.1126/science.1200807, 2011.

Leyden, B. W.: Late Quaternary aridity and Holocene moisture fluctuations in the Lake Valencia Basin, Venezuela, Ecology, 66, 1279, doi:10.2307/1939181, 1985.

Li, B., Nychka, D. W., and Ammann, C. M.: The value of multiproxy reconstruction of past climate, J. Am. Stat. Assoc., 105, 883–895, 2010.

Li, W. and Fu, R.: Influence of cold air intrusions on the wet season onset over Amazonia, J. Climate, 19, 257–275, 2006.

Liebmann, B. and Marengo, J.: Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin, J. Climate, 14, 4308–4318, doi:10.1175/1520-0442(2001)014<4308:IVOTRS>2.0.CO;2, 2001.

Maldonado, A. and Villagrán, C.: Climate variability over the last 9900 cal yr BP from a swamp forest pollen record along the semiarid coast of Chile, Quaternary Res., 66, 246–258, doi:10.1016/j.yqres.2006.04.003, 2006.

Mancini, M. V.: Variabilidad climática durante los últimos 1000 años en el área de Cabo Vírgenes, Argentina, Ameghiniana, 44, 173–182, 2007.

Mancini, M. V.: Holocene vegetation and climate changes from a peat pollen record of the forest–steppe ecotone, southwest of Patagonia (Argentina), Quaternary Sci. Rev., 28, 1490–1497, doi:10.1016/j.quascirev.2009.01.017, 2009.





CPD
11, 3475–3565, 2015

Mancini, M. V. and Graham, M.: Registros polínicos de depósitos del Holoceno en el sudeste de Patagonia, Argentina: su aplicación en la reconstrucción paleoambiental, Ameghiniana, 51, 194–208, doi:10.5710/AMGH.01.01.2014.1068, 2014.

Mancini, M. V., Paez, M. M., and Prieto, A. R.: Cambios paleoambientales durante los ultimos 7.000 14C años en el ecotono bosque'estepa, 47–48° S, Santa Cruz, Argentina, Ameghiniana, 39, 151–162, 2002.

Marchant, R., Behling, H., Berrio, J. C., Cleef, A., Duivenvoorden, J., Hooghiemstra, H., Kuhry, P., Melief, B., Van Geel, B., and Van der Hammen, T.: Mid-to Late-Holocene pollen-based biome reconstructions for Colombia, Quaternary Sci. Rev., 20, 1289–1308, 2001.

Marchant, R., Almeida, L., Behling, H., Berrio, J. C., Bush, M., Cleef, A., Duivenvoorden, J., Kappelle, M., De Oliveira, P., Teixeira de Oliveira-Filho, A., Lozano-García, S., Hooghiemstra, H., Ledru, M. P., Ludlow-Wiechers, B., Markgraf, V., Mancini, V., Paez, M., Prieto, A., Rangel, O., and Salgado-Labouriau, M. L.: Distribution and ecology of parent taxa of pollen lodged within the Latin American Pollen Database, Rev. Palaeobot. Palyno., 121, 1–75, 2002.

Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., Sampaio de Oliveira, G., de Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F.: The drought of Amazonia in 2005, J. Climate, 21, 495–516, doi:10.1175/2007JCLI1600.1, 2008.

Markgraf, V., Webb, R. S., Anderson, K. H., and Anderson, L.: Modern pollen/climate calibration for southern South America, Palaeogeogr. Palaeocl., 181, 375–397, 2002.

Markgraf, V., Whitlock, C., and Haberle, S.: Vegetation and fire history during the last 18,000 cal yr B. P. in southern Patagonia: Mallín Pollux, Coyhaique, Province Aisén (45°41′30″ S, 71°50′30″ W, 640 m elevation), Palaeogeogr. Palaeocl., 254, 492–507, doi:10.1016/j.palaeo.2007.07.008, 2007.

Mauquoy, D., Blaauw, M., Van Geel, B., Borromei, A., Quattrocchio, M., Chambers, F. M., and Possnert, G.: Late Holocene climatic changes in Tierra del Fuego based on multiproxy analyses of peat deposits, Quaternary Res., 61, 148–158, doi:10.1016/j.yqres.2003.10.001, 2004.

Mayle, F. E. and Iriarte, J.: Integrated palaeoecology and archaeology – a powerful approach for understanding pre-Columbian Amazonia, J. Archaeol. Sci., 51, 54–64, doi:10.1016/j.jas.2012.08.038, 2014.

Mayle, F. E., Burbridge, R., and Killeen, T. J.: Millennial-scale dynamics of southern Amazonian rain forests, Science, 290, 2291–2294, doi:10.1126/science.290.5500.2291, 2000.

Mayr, C., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Maidana, N. I., Ohlendorf, C., Schäbitz, F., Schleser, G. H., Struck, U., Wille, M., and Zolitschka, B.: Palaeoenvironmental changes in southern Patagonia during the last millennium recorded in lake sediments from Laguna Azul (Argentina), Palaeogeogr. Palaeocl., 228, 203–227, doi:10.1016/j.palaeo.2005.06.001, 2005.

McGlue, M. M., Silva, A., Zani, H., Corradini, F. A., Parolin, M., Abel, E. J., Cohen, A. S., Assine, M. L., Ellis, G. S., Trees, M. A., Kuerten, S., dos Santos Gradella, F. G., and Rasbold, G. G.: Lacustrine records of Holocene flood pulse dynamics in the upper Paraguay River watershed (Pantanal wetlands, Brazil), Quaternary Res., 78, 285–294, doi:10.1016/j.yqres.2012.05.015, 2012.

Montecinos, A. and Aceituno, P.: Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies, J. Climate, 16, 281–296, doi:10.1175/1520-0442(2003)016<0281:SOTERR>2.0.CO;2, 2003.

Montoya, E. and Rull, V.: Gran Sabana fires (SE Venezuela): a paleoecological perspective, Quaternary Sci. Rev., 30, 3430–3444, doi:10.1016/j.quascirev.2011.09.005, 2011.

Montoya, E., Rull, V., Nogué, S., and Díaz, W. A.: Paleoecología del Holoceno en la Gran Sabana, SE Venezuela: análisis preliminar de polen y microcarbones en la Laguna Encantada, Collectanea Botanica, 28, 65–79, doi:10.3989/collectbot.2008.v28.005, 2009.

Montoya, E., Rull, V., Stansell, N. D., Abbott, M. B., Nogué, S., Bird, B. W., and Díaz, W. A.: Forest–savanna–morichal dynamics in relation to fire and human occupation in the southern Gran Sabana (SE Venezuela) during the last millennia, Quaternary Res., 76, 335–344, doi:10.1016/j.yqres.2011.06.014, 2011a.

Montoya, E., Rull, V., Stansell, N. D., Bird, B. W., Nogué, S., Vegas-Vilarrúbia, T., Abbott, M. B., and Díaz, W. A.: Vegetation changes in the neotropical Gran Sabana (Venezuela) around the Younger Dryas chron, J. Quaternary Sci., 26, 207–218, doi:10.1002/jqs.1445, 2011b.

Moreno, P. I., François, J. P., Villa-Martínez, R. P., and Moy, C. M.: Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia, Quaternary Sci. Rev., 28, 25–38, doi:10.1016/j.quascirev.2008.10.009, 2009.

Moreno, P. I., Vilanova, I., Villa-Martínez, R., Garreaud, R. D., Rojas, M., and De Pol-Holz, R.: Southern Annular Mode-like changes in southwestern Patagonia at centennial timescales over the last three millennia, Nature Communications, 5, 4375, doi:10.1038/ncomms5375, 2014.

Moscol-Olivera, M. C. and Hooghiemstra, H.: Three millennia upper forest line changes in northern Ecuador: pollen records and altitudinal vegetation distributions, Rev. Palaeobot. Palyno., 163, 113–126, doi:10.1016/j.revpalbo.2010.10.003, 2010.





CPD
11, 3475–3565, 2015

Moscol Olivera, M. C. and Hooghiemstra, H.: Three millennia upper forest line changes in northern Ecuador: pollen records and altitudinal vegetation distributions, Rev. Palaeobot. Palyno., 163, 113–126, doi:10.1016/j.revpalbo.2010.10.003, 2010.

Neukom, R. and Gergis, J.: Southern Hemisphere high-resolution palaeoclimate records of the last 2000 years, Holocene, 22, 501–524, doi:10.1177/0959683611427335, 2012.

Neukom, R., Luterbacher, J., Villalba, R., Küttel, M., Frank, D., Jones, P. D., Grosjean, M., Esper, J., Lopez, L., and Wanner, H.: Multi-centennial summer and winter precipitation variability in southern South America: south American precipitation variability, Geophys. Res. Lett., 37, L14708, doi:10.1029/2010GL043680, 2010.

Niemann, H. and Behling, H.: Late Holocene environmental change and human impact inferred from three soil monoliths and the Laguna Zurita multi-proxi record in the southeastern Ecuadorian Andes, Veg. Hist. Archaeobot., 19, 1–15, doi:10.1007/s00334-009-0226-6, 2010.

Niemann, H., Matthias, I., Michalzik, B., and Behling, H.: Late Holocene human impact and environmental change inferred from a multi-proxy lake sediment record in the Loja region, southeastern Ecuador, Quatern. Int., 308–309, 253–264, doi:10.1016/j.quaint.2013.03.017, 2013.

Nobre, P. and Shukla, J.: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America, J. Climate, 9, 2464–2479, doi:10.1175/1520-0442(1996)009<2464:VOSSTW>2.0.CO;2, 1996.

Nogué, S., Rull, V., Montoya, E., Huber, O., and Vegas-Vilarrúbia, T.: Paleoecology of the Guayana Highlands (northern South America): Holocene pollen record from the Eruoda-tepui, in the Chimantá Massif, Palaeogeogr. Palaeocl., 281, 165–173, doi:10.1016/j.palaeo.2009.07.019, 2009.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., and Kassem, K. R.: Terrestrial ecoregions of the world: a new map of life on Earth, BioScience, 51, 933–938, doi:10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2, 2010.

PAGES-2 k Consortium: Continental-scale temperature variability during the past two millennia, Nat. Geosci., 6, 339–346, doi:10.1038/ngeo1797, 2013.





CPD

11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀| |▶

◀ ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Pesce, O. H. and Moreno, P. I.: Vegetation, fire and climate change in central-east Isla Grande de Chiloé (43° S) since the Last Glacial Maximum, northwestern Patagonia, Quaternary Sci. Rev., 90, 143–157, doi:10.1016/j.quascirev.2014.02.021, 2014.

Polissar, P. J., Abbott, M. B., Wolfe, A. P., Bezada, M., Rull, V., and Bradley, R. S.: Solar modulation of Little Ice Age climate in the tropical Andes, P. Natl. Acad. Sci. USA, 103, 8937–8942, doi:10.1073/pnas.0603118103, 2006.

Punyasena, S. W.: Estimating Neotropical palaeotemperature and palaeoprecipitation using plant family climatic optima, Palaeogeogr. Palaeocl., 265, 226–237, doi:10.1016/j.palaeo.2008.04.025, 2008.

Punyasena, S. W., Eshel, G., and McElwain, J. C.: The influence of climate on the spatial patterning of Neotropical plant families, J. Biogeogr., 35, 117–130, doi:10.1111/j.1365-2699.2007.01773.x, 2008.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, J. Geophys. Res.-Atmos., 108, 4407, doi:10.1029/2002JD002670, 2003.

Rodbell, D. T.: An 15,000-year record of El Niño-driven alluviation in southwestern Ecuador, Science, 283, 516–520, doi:10.1126/science.283.5401.516, 1999.

Ronchail, J., Cochonneau, G., Molinier, M., Guyot, J.-L., De Miranda Chaves, A. G., Guimarães, V., and de Oliveira, E.: Interannual rainfall variability in the Amazon Basin and sea-surface temperatures in the equatorial Pacific and the tropical Atlantic oceans, Int. J. Climatol., 22, 1663–1686, doi:10.1002/joc.815, 2002.

Roucoux, K. H., Lawson, I. T., Jones, T. D., Baker, T. R., Coronado, E. N. H., Gosling, W. D., and Lähteenoja, O.: Vegetation development in an Amazonian peatland, Palaeogeogr. Palaeocl., 374, 242–255, doi:10.1016/j.palaeo.2013.01.023, 2013.

Rull, V.: Contribución a la paleoecología de Pantepui la Gran Sabana (Guayana Venezolana): clima, biogeografía, y ecología, Scientia Guaianae, 2, 1–133, 1991.

Rull, V.: A palynological record of a secondary succession after fire in the Gran Sabana, Venezuela, J. Quaternary Sci., 14, 137–152, 1999.

Rull, V.: An evaluation of the Lost World and Vertical Displacement hypotheses in the Chimantá Massif, Venezuelan Guayana, Global Ecol. Biogeogr., 13, 141–148, doi:10.1111/j.1466-882X.2004.00073.x, 2004a.



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

Rull, V.: Is the “Lost World” really lost? Palaeoecological insights into the origin of the peculiar flora of the Guayana Highlands, Naturwissenschaften, 91, 139–142, doi:10.1007/s00114-004-0504-1, 2004b.
Rull, V.: Palaeovegetational and palaeoenvironmental trends in the summit of the Guaiquinima Massif (Venezuelan Guayana) during the Holocene, J. Quaternary Sci., 20, 135–145, doi:10.1002/jqs.896, 2005a.
Rull, V.: Vegetation and environmental constancy in the Neotropical Guayana Highlands during the last 6000 years?, Rev. Palaeobot. Palyno., 135, 205–222, doi:10.1016/j.revpalbo.2005.03.008, 2005b.
Rull, V.: Long-term vegetation stability and the concept of potential natural vegetation in the Neotropics, J. Veg. Sci., 26, 603–607, doi:10.1111/jvs.12278, 2015.
Rull, V. and Montoya, E.: Mauritia flexuosa palm swamp communities: natural or human-made? A palynological study of the Gran Sabana region (northern South America) within a neotropical context, Quaternary Sci. Rev., 99, 17–33, doi:10.1016/j.quascirev.2014.06.007, 2014.
Rull, V. and Schubert, C.: The little ice age in the tropical Venezuelan Andes, Acta Científica Venez., 40, 71–73, 1989.
Rull, V., Salgado-Labouriau, M. L., Schubert, C., and Valastro Jr., S.: Late Holocene temperature depression in the Venezuelan Andes: palynological evidence, Palaeogeogr. Palaeocl., 60, 109–121, 1987.
Rull, V., Vegas, T., Nogué, S., and Montoya, E.: Bureaucratic obstruction of conservation science in the Guayana Highlands, Conserv. Biol., 22, 508–509, doi:10.1111/j.1523-1739.2008.00960.x, 2008.
Rull, V., Montoya, E., Nogué, S., and Huber, O.: Preliminary palynological analysis of a Holocene peat bog from Apakará-tepui (Chimantá Massif, Venezuelan Guayana), Collectanea Botanica, 30, 79–88, doi:10.3989/collectbot.2011.v30.008, 2011.
Rull, V., Montoya, E., Nogué, S., Vegas-Vilarrúbia, T., and Safont, E.: Ecological palaeoecology in the neotropical Gran Sabana region: long-term records of vegetation dynamics as a basis for ecological hypothesis testing, Perspect. Plant Ecol., 15, 338–359, doi:10.1016/j.ppees.2013.07.004, 2013.
Safont, E., Rull, V., Vegas-vilarrúbia, T., k Holst, B., Huber, O., Nozawa, S., Vivas, Y., and Silva, A.: Establishing a baseline of plant diversity and endemism on a neotropical mountain summit for future comparative studies assessing upward migration: an

approach from biogeography and nature conservation, Syst. Biodivers., 12, 292–314, doi:10.1080/14772000.2014.918061, 2014.

Schäbitz, F., Wille, M., Francois, J.-P., Haberzettl, T., Quintana, F., Mayr, C., Lücke, A., Ohlendorf, C., Mancini, V., Paez, M. M., Prieto, A. R., and Zolitschka, B.: Reconstruction of palaeoprecipitation based on pollen transfer functions – the record of the last 16 ka from Laguna Potrok Aike, southern Patagonia, Quaternary Sci. Rev., 71, 175–190, doi:10.1016/j.quascirev.2012.12.006, 2013.

Schittek, K., Forbriger, M., Mächtle, B., Schäbitz, F., Wennrich, V., Reindel, M., and Eitel, B.: Holocene environmental changes in the highlands of the southern Peruvian Andes (14° S) and their impact on pre-Columbian cultures, Clim. Past, 11, 27–44, doi:10.5194/cp-11-27-2015, 2015.

Silverman, H.: Andean Archaeology III: North and South, Springer, USA, 2008.

Silvestri, G. E. and Vera, C. S.: Antarctic Oscillation signal on precipitation anomalies over southeastern South America, Geophys. Res. Lett., 30, 2115, doi:10.1029/2003GL018277, 2003.

Stutz, S., Borel, C. M., Fontana, S. L., and Tonello, M. S.: Holocene changes in trophic states of shallow lakes from the Pampa plain of Argentina, Holocene, 22, 1263–1270, doi:10.1177/0959683612446667, 2012.

Stutz, S., Tonello, M. S., Gonzalez Sagraria, M. A., Navarro, D., and Fontana, S.: Historia ambiental de los lagos someros de la llanura Pampeana desde el Holoceno medio. Inferencias paleoclimáticas, Lat. Am. J. Sedimentol. Basin Anal., in press, 2015.

Takahashi, K.: The atmospheric circulation associated with extreme rainfall events in Piura, Peru, during the 1997–1998 and 2002 El Niño events, Ann. Geophys., 22, 3917–3926, doi:10.5194/angeo-22-3917-2004, 2004.

Thomas, D. J.: Order Without Government: the Society of the Pemons Indians of Venezuela, University of Illinois Press, Illinois, 1982.

Thompson, D. W. J. and Wallace, J. M.: Annular modes in the extratropical circulation. Part I: Month-to-month variability*, J. Climate, 13, 1000–1016, doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2, 2000.

Tonello, M. S. and Prieto, A. R.: Modern vegetation–pollen–climate relationships for the Pampa grasslands of Argentina, J. Biogeogr., 35, 926–938, doi:10.1111/j.1365-2699.2007.01854.x, 2008.

Tonello, M. S., Mancini, M. V., and Seppä, H.: Quantitative reconstruction of Holocene precipitation changes in southern Patagonia, Quaternary Res., 72, 410–420, doi:10.1016/j.yqres.2009.06.011, 2009.
Tonello, M. S., Mancini, M. V., de Porras, M. E., Bamonte, F. P., and Sottile, G.: Pollen and climate dataset at southern Patagonia: evaluating weaknesses and strengths for quantitative palaeoclimatic reconstructions, presented at II International Symposium "Reconstructing Climate Variations in South America and the Antarctic Peninsula over the last 2000 years", 27–30 October, Valdivia, Chile, 2010.
Urrego, D. H., Bush, M. B., and Silman, M. R.: A long history of cloud and forest migration from Lake Consuelo, Peru, Quaternary Res., 73, 364–373, doi:10.1016/j.yqres.2009.10.005, 2010.
Urrego Giraldo, L. E. and Berrio M., J. C.: Los estudios paleoecológicos en el Choco Biogeográfico durante el Holoceno medio y reciente, in: Diversidad Biótica IV. El chocó Biogeográfico/Costa Pacífica, edited by: Rangel-Ch., J. O., Universidad Nacional de Colombia, Instituto de Ciencias Naturales, Conservación Internacional, Bogotá, D.C., Colombia, 23–38, 2011.
Urrego Giraldo, L. E. and del Valle Arango., J. I.: Reconstrucción de la sucesión de un bosque de "Guandal" (Pacífico Colombiano) durante el Holoceno reciente, Caldasia, 24, 425–443, 2002.
Valencia, B. G., Urrego, D. H., Silman, M. R., and Bush, M. B.: From ice age to modern: a record of landscape change in an Andean cloud forest: cloud forest history: from ice age to modern, J. Biogeogr., 37, 1637–1647, doi:10.1111/j.1365-2699.2010.02318.x, 2010.
Van der Hammen, T. and Correal Urrego, G.: Prehistoric man of the Sabana de Bogotá: data for an ecological prehistory, Palaeogeogr. Palaeocl., 25, 179–190, doi:10.1016/0031-0182(78)90077-9, 1978.
Van Geel, B. and Van der Hammen, T.: Upper Quaternary vegetational and climatic secuense of the Fuquene area (eastern Cordillera, Colombia), Palaeogeogr. Palaeocl., 14, 9–92, 1973.
van Oldenborgh, G. J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., Hazeleger, W., and Dijkstra, H.: Western Europe is warming much faster than expected, Clim. Past, 5, 1–12, doi:10.5194/cp-5-1-2009, 2009.
Vélez, M. I., Wille, M., Hooghiemstra, H., Metcalfe, S., Vandenberghe, J., and Van der Borg, K.: Late Holocene environmental history of southern Chocó region, Pacific Colombia; sediment, diatom and pollen analysis of core El Caimito, Palaeogeogr. Palaeocl., 173, 197–214, 2001.

Viglizzo, E. F. and Frank, F. C.: Ecological interactions, feedbacks, thresholds and collapses in the Argentine Pampas in response to climate and farming during the last century, Quatern. Int., 158, 122–126, doi:10.1016/j.quaint.2006.05.022, 2006.

Villalba, R., Grosjean, M., and Kiefer, T.: Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): state of the art and perspectives, Palaeogeogr. Palaeocl., 281, 175–179, doi:10.1016/j.palaeo.2009.08.007, 2009.

Villa-Martínez, R., Villagrán, C., and Jenny, B.: Pollen evidence for late-Holocene climatic variability at Laguna de Aculeo, Central Chile (lat. 34° S), Holocene, 14, 361–367, doi:10.1191/0959683604hl712rp, 2004.

Vuille, M. and Garreaud, R. D.: Ocean–atmosphere interactions on interannual to decadal timescales, in: Handbook of Environmental Change, vol. 1, edited by: Matthews, J. A., Bartlein, P. J., Briffa, K. R., Dawson, A., de Vernal, A., Denham, T., Fritz, S. C., and Oldfield, F., Sage Publications, London, Los Angeles, New Delhi, Singapore, 2012.

Vuille, M., Bradley, R. S., and Keimig, F.: Interannual climate variability in the central Andes and its relation to tropical Pacific and Atlantic forcing, J. Geophys. Res.-Atmos., 105, 12447–12460, doi:10.1029/2000JD900134, 2000.

Vuille, M., Burns, S. J., Taylor, B. L., Cruz, F. W., Bird, B. W., Abbott, M. B., Kanner, L. C., Cheng, H., and Novello, V. F.: A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia, Clim. Past, 8, 1309–1321, doi:10.5194/cp-8-1309-2012, 2012.

Wang, H. and Fu, R.: Cross-equatorial flow and seasonal cycle of precipitation over South America, J. Climate, 15, 1591–1608, 2002.

Weng, C., Bush, M. B., and Athens, J. S.: Holocene climate change and hydrarch succession in lowland Amazonian Ecuador, Rev. Palaeobot. Palyno., 120, 73–90, 2002.

Whitlock, C., Bianchi, M. M., Bartlein, P. J., Markgraf, V., Marlon, J., Walsh, M., and McCoy, N.: Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41–42.5° S), Argentina, Quaternary Res., 66, 187–201, doi:10.1016/j.yqres.2006.04.004, 2006.

Whitney, B. S., Mayle, F. E., Punyasena, S., Fitzpatrick, K., Burn, M., Guillen, R., Chavez, E., Mann, D., Pennington, R. T., and Metcalfe, S.: A 45 kyr palaeoclimate record from the lowland interior of tropical South America, Palaeogeogr. Palaeocl., 307, 177–192, doi:10.1016/j.palaeo.2011.05.012, 2011.

Whitney, B. S., Dickau, R., Mayle, F. E., Soto, J. D., and Iriarte, J.: Pre-Columbian landscape impact and agriculture in the Monumental Mound region of the Llanos de Moxos, lowland Bolivia, Quaternary Res., 80, 207–217, doi:10.1016/j.yqres.2013.06.005, 2013.

Whitney, B. S., Dickau, R., Mayle, F. E., Walker, J. H., Soto, J. D., and Iriarte, J.: Pre-Columbian raised-field agriculture and land-use in the Bolivian Amazon, Holocene, 24, 231–241, 2014.

Winsborough, B. M., Shimada, I., Newsom, L. A., Jones, J. G., and Segura, R. A.: Paleoenvironmental catastrophies on the Peruvian coast revealed in lagoon sediment cores from Pachacamac, J. Archaeol. Sci., 39, 602–614, doi:10.1016/j.jas.2011.10.018, 2012.

Wille, M. and Hooghiemstra, H.: Paleoenvironmental history of the Popayán area since 27 000 yr BP at Timbio, southern Colombia, Rev. Palaeobot. Palyno., 109, 45–63, 2000.

Wille, M., Hooghiemstra, H., Van Geel, B., Behling, H., de Jong, A., and Van der Borg, K.: Submillennium-scale migrations of the rainforest–savanna boundary in Colombia: $^{14}C$ wiggle-matching and pollen analysis of core Las Margaritas, Palaeogeogr. Palaeocl., 193, 201–223, doi:10.1016/S0031-0182(03)00226-8, 2003.

Wille, M., Maidana, N. I., Schäbitz, F., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schleser, G. H., and Zolitschka, B.: Vegetation and climate dynamics in southern South America: the microfossil record of Laguna Potrok Aike, Santa Cruz, Argentina, Rev. Palaeobot. Palyno., 146, 234–246, doi:10.1016/j.revpalbo.2007.05.001, 2007.

Zárate, M. A. and Tripaldi, A.: The aeolian system of central Argentina, Aeolian Res., 3, 401–417, doi:10.1016/j.aeolia.2011.08.002, 2012.

Zhou, J. and Lau, K.-M.: Principal modes of interannual and decadal variability of summer rainfall over South America, Int. J. Climatol., 21, 1623–1644, doi:10.1002/joc.700, 2001.





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

**Table 1.** Climate modes used relevant for South America.

| Abbreviation | Mode | Methods | Description | Reference |
|---|---|---|---|---|
| Niño 3.4 | Niño3.4 index | SST averaged over 5° N–5° S, 170–120° W calculated from Hadisst data | Describes interannual (2–7 years) variability of tropical Pacific SST | Rayner et al. (2003) |
| AMO | Atlantic Multidecadal Oscillation | Defined as the area-averaged SST in the Atlantic north of the equator, calculated from Kaplan SST V2 | Describes coherent variations in North Atlantic SST on multidecadal (50–70 years) time scales | Enfield et al. (2001) |
| IPO | Interdecadal Pacific Oscillation | Multidecadal Pacific-wide mode of SST variability, calculated as the 2nd EOF of low-frequency filtered HadSST data | Describes joint variations of Pacific SST in both hemispheres on multidecadal (20–30 years) time scale | Folland et al. (2002) |
| SAM | Southern Annular Mode or Antarctic Oscillation | Calculated as leading principal component (PC) of 850 hPa geopotential height anomalies south of 20° S | Determines strength and location of circumpolar vortex (location of the extratropical westerly storm tracks) | Thompson and Wallace (2000) |
| TNA | Tropical North Atlantic SST | Defined as SST averaged over 5.5–23.5° N, 15–57.5° W and calculated from HadISST and NOAA OI 1 × 1 datasets | Describes interannual variability of SST variations in the tropical North Atlantic | Enfield et al. (1999) |
| TSA | Tropical South Atlantic SST | Defined as SST averaged over −20° S, 10° E–30° W (TSA), calculated from HadISST and NOAA OI 1 × 1 datasets | Describes interannual variability of SST variations in the tropical South Atlantic | Enfield et al. (1999) |





CPD
11, 3475–3565, 2015

**Table 2.** Comparison of PAGES 2 k criteria with criteria implemented in this study.

| Criteria | PAGES 2 k | This paper | Criteria abbreviation |
|---|---|---|---|
| A | Described in peer-reviewed publication | Described in peer-reviewed publication | |
| B | Minimum duration of record ≥ 500 years | Minimum duration of record ≥ 500 years | |
| 1 | Not specified | More than 2 chronological tie-points within the last 2 ka | CONTROL2 |
| 2 | Resolution ≤ 50 years | Resolution ≤ 200 years* | RES200 |
| 3 | Tie points near the end part of the records and one near the oldest part | Tie points near the end part of the records and one near the oldest part | TOP-END |
| 4 | Records longer than 1 ka must include min. 1 additional age midway between the other two. | Records longer than 1 ka must include min. 1 additional age midway between the other two. | 1000-MID |

* Flexible criteria of 200–300 years



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

**Table 3.** List of pollen records used and metadata.

| Fig. 6 | Region | LAPD ID | Site Name | Potentially suitable for 2 k climate modelling | Potentially suitable for human studies | LOTRED-2 k | DUR 500 | CONTROL2 | TOP_END | 1000_MID3 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Ven.Guy | 1638 | Laguna Encantada PATAM4-D07 | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| A | Ven.Guy | 1247 | Eruoda PATAM6-A07 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| A | Ven.Guy | 1606 | Churi Chim-2 | 1 | 0 | 2 | 1 | 1 | 0 | 0 |
| A | Ven.Guy | 1582 | Apakará PATAM9-A07 | 1 | 0 | 3 | 1 | 1 | 1 | 0 |
| A | Ven.Guy | 1684 | Urué | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| A | Ven.Guy | 1646 | Lake Chonita PARAM1-B07 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| A | Ven.Guy | 1611 | El Paují PATAM5-A07 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| B | N-Andes | 1648 | Lake Valencia 76V 1-5 | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 1665 | Piedras Blancas | 1 | 0 | 2 | 1 | 1 | 0 | 0 |
| B | N-Andes | 0892 | Fúquene-2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| B | N-Andes | 0899 | Pantano de Genagra | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| B | N-Andes | 0851 | Carimagua Bosque | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 0938 | Las Margaritas | 1 | 1 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 0941 | Loma Linda | 0 | 1 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 0907 | Jotaordo | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 0877 | El Caimito | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 0901 | Guandal | 1 | 1 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 9035 | Piusbi | 0 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 0910 | La Cocha 1 | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 1867 | Reserve Guandera-G15 | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| B | N-Andes | 1176 | Reserve Guandera-G8 | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 1751 | Laguna Daniel Alvarez | 0 | 1 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 1158 | Laguna Pallcacocha 1 | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 2143 | Papallacta PA 1-08 | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 1181 | Tres Lagunas | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| B | N-Andes | 1160 | Laguna Zurita | 0 | 1 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 1749 | ECSF Refugio | 1 | 0 | 3 | 1 | 1 | 1 | 0 |
| B | N-Andes | 1144 | El Junco EJ1 | 0 | 1 | 3 | 1 | 1 | 1 | 0 |
| C | C-Andes | 2518 | Cerro Llamoca | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| C | C-Andes | 1520 | Marcacocha | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| C | C-Andes | 1496 | Chica-Soras | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| C | C-Andes | 1516 | Pacucha | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| C | C-Andes | 1514 | Consuelo | 1 | 0 | 2 | 1 | 1 | 0 | 0 |
| C | C-Andes | 1555 | Urpi Cocha Lagoon Core 2 | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| C | C-Andes | 1546 | Nevado Coropuna | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| D | Amazon | 1211 | Quistococha | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| D | Amazon | 1558 | Werth | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| D | Amazon | 2991 | Laguna Granja | 0 | 1 | 4 | 1 | 1 | 1 | 1 |
| D | Amazon | 0460 | Fazenda Cigana | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| D | Amazon | 3004 | French Guiana K-VIII | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| D | Amazon | 1498 | Gentry | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| D | Amazon | 1549 | Parker | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| D | Amazon | 0518 | Lake Geral C | 0 | 1 | 1 | 1 | 0 | 0 | 0 |





CPD
11, 3475–3565, 2015

**Table 3.** Continued.

| Fig. 6 | Region | LAPD ID | Site Name | Human Indicators | First human indicator (cal yr BP) | Precip. Sensitive | Temp. Sensitive |
|---|---|---|---|---|---|---|---|
| A | Ven.Guy | 1638 | Laguna Encantada PATAM4-D07 | Fire, Mauritia(?) | 1200 | X | |
| A | Ven.Guy | 1247 | Eruoda PATAM6-A07 | No | | X | |
| A | Ven.Guy | 1606 | Churi Chim-2 | No | | X | X |
| A | Ven.Guy | 1582 | Apakará PATAM9-A07 | No | | X | |
| A | Ven.Guy | 1684 | Urué | Possible fire increase | 2000 | X | |
| A | Ven.Guy | 1646 | Lake Chonita PARAM1-B07 | Mauritia, fire increase | 2000 | X | |
| A | Ven.Guy | 1611 | El Paují PATAM5-A07 | Forest composition change, fire increase | > 2000 | X | |
| B | N-Andes | 1648 | Lake Valencia 76V 1-5 | No | | | |
| B | N-Andes | 1665 | Piedras Blancas | No | | | |
| B | N-Andes | 0892 | Fúquene-2 | Increase Asteraceae, Poaceae | 3000 | | |
| B | N-Andes | 0899 | Pantano de Genagra | Deforestation, pollen of *Z. mays*, Spermacoce, Cheno/Am; spores of *Grammitis*-type and Anthoceros | 2300 | | X |
| B | N-Andes | 0851 | Carimagua Bosque | Mauritiella, savanna, *Cecropia* increase | 200 | X | |
| B | N-Andes | 0938 | Las Margaritas | Savanna increase | | | |
| B | N-Andes | 0941 | Loma Linda | Savanna increase | | X | |
| B | N-Andes | 0907 | Jotaordo | *Zea mays* and palm increase | 1000 | X | |
| B | N-Andes | 0877 | El Caimito | *Cecropia* and palm trees (Arecaceae) | 580 | X | |
| B | N-Andes | 0901 | Guandal | *Cecropia*, *Vismia*, other indicators of intervened swamps | 600 | X | |
| B | N-Andes | 9035 | Piusbi | *Zea mays* | 1800 | X | |
| B | N-Andes | 0910 | La Cocha 1 | Logging, preferentially *Podocarpus*, frequent fires, forest disturbance and changes of the diatom flora. | 1405–1100 | X | X |
| B | N-Andes | 1867 | Reserve Guandera-G15 | *Rumex* | 100 | X | |
| B | N-Andes | 1176 | Reserve Guandera-G8 | Dodonaea presence | 300 | | |
| B | N-Andes | 1751 | Laguna Daniel Alvarez | *Zea mays* | 1400 | | |
| B | N-Andes | 1158 | Laguna Pallcacocha 1 | No | | X | |
| B | N-Andes | 2143 | Papallacta PA 1-08 | No | | X | |
| B | N-Andes | 1181 | Tres Lagunas | *Zea mays* | 300 | | |
| B | N-Andes | 1160 | Laguna Zurita | *Zea mays* | 900 | | |
| B | N-Andes | 1749 | ECSF Refugio | Decrease *Isoetes* and Cyperaceae (due to moisture increase or humans), *Z. mays* (800 cal yr) | 1200 | | |
| B | N-Andes | 1144 | El Junco EJ1 | No | | | |
| C | C-Andes | 2518 | Cerro Llamoca | No | | X | |
| C | C-Andes | 1520 | Marcacocha | *Zea mays* | 2700 | X | X |
| C | C-Andes | 1496 | Chica-Soras | Chen/Am (expansion *Quinoa* crops?) | 1000 | | |
| C | C-Andes | 1516 | Pacucha | *Zea mays* | 5500 | X | |
| C | C-Andes | 1514 | Consuelo | No | | X | |
| C | C-Andes | 1555 | Urpi Cocha Lagoon Core 2 | *Zea mays* | > 2000 | | |
| C | C-Andes | 1546 | Nevado Coropuna | *Zea mays*, *Ambrosia* (terrace consolidator) | 2200 | X | X |
| D | Amazon | 1211 | Quistococha | No | | | |
| D | Amazon | 1558 | Werth | No | | X | |
| D | Amazon | 2991 | Laguna Granja | *Z. mays*, charcoal | 2500 | X? | |
| D | Amazon | 0460 | Fazenda Cigana | Charcoal, forest decrease, savanna increase | > 2000? | X | |
| D | Amazon | 3004 | French Guiana K-VIII | *Z. mays*, *Manihot esculenta*, Crantz and *Ipomoea batatas* | 800–200 | ? | ? |
| D | Amazon | 1498 | Gentry | *Z. mays*, *Manihot esculenta*, *Cecropia* | ca. 3500–500 | | |
| D | Amazon | 1549 | Parker | Cyperaceae, charcoal | ca. 2800 | X | |
| D | Amazon | 0518 | Lake Geral C | *Z. mays*, *Cecropia*, Gramineae, charcoal (?) | ca. 3350 (ca. 5500) | X | |

**Table 3.** Continued.

| Fig. 6 | Region | LAPD ID | Site Name | References | Latitude (decimal degrees) | Longitude (decimal degrees) |
|---|---|---|---|---|---|---|
| A | Ven.Guy | 1638 | Laguna Encantada PATAM4-D07 | Montoya et al. (2009) | 4.60 | −61.11 |
| A | Ven.Guy | 1247 | Eruoda PATAM6-A07 | Nogue et al. (2009) | 5.37 | −62.08 |
| A | Ven.Guy | 1606 | Churi Chim-2 | Rull (1991, 2004a, b) | 5.32 | −62.17 |
| A | Ven.Guy | 1582 | Apakará PATAM9-A07 | Rull et al. (2011) | 5.32 | −62.23 |
| A | Ven.Guy | 1684 | Urué | Rull (1991, 1999) | 5.03 | −61.17 |
| A | Ven.Guy | 1646 | Lake Chonita PARAM1-B07 | Montoya et al. (2011a) | 4.65 | −61.00 |
| A | Ven.Guy | 1611 | El Paují PATAM5-A07 | Montoya et al. (2011b) | 4.28 | −61.35 |
| B | N-Andes | 1648 | Lake Valencia 76V 1-5 | Leyden (1985) | 10.18 | −67.01 |
| B | N-Andes | 1665 | Piedras Blancas | Rull et al. (1987) | 9.17 | −70.83 |
| B | N-Andes | 0892 | Fúquene-2 | Van Geel and Van der Hammen (1973) | 5.45 | −73.77 |
| B | N-Andes | 0899 | Pantano de Genagra | Behling et al. (2001) | 2.47 | −76.62 |
| B | N-Andes | 0851 | Carimagua Bosque | Berrio et al. (2000) | 4.07 | −70.22 |
| B | N-Andes | 0938 | Las Margaritas | Wille et al. (2003) | 3.38 | −73.43 |
| B | N-Andes | 0941 | Loma Linda | Behling and Hooghiemstra (2000) | 3.30 | −73.38 |
| B | N-Andes | 0907 | Jotaordo | Berrio et al. (2000), Urrego and Berrio (2011) | 5.80 | −76.70 |
| B | N-Andes | 0877 | El Caimito | Velez et al. (2001) | 2.53 | −77.60 |
| B | N-Andes | 0901 | Guandal | Urrego and del Valle (2002) | 2.22 | −78.35 |
| B | N-Andes | 9035 | Piusbi | Behling et al. (1998a) | 1.90 | −77.94 |
| B | N-Andes | 0910 | La Cocha 1 | Gonzalez-Carranza et al. (2012) | 1.06 | −77.15 |
| B | N-Andes | 1867 | Reserve Guandera-G15 | Bakker et al. (2008) | 0.60 | −77.70 |
| B | N-Andes | 1176 | Reserve Guandera-G8 | Moscol Olivera and Hooghiemstra (2010) | 0.60 | −77.70 |
| B | N-Andes | 1751 | Laguna Daniel Alvarez | Niemann et al. (2013) | −4.02 | −79.21 |
| B | N-Andes | 1158 | Laguna Pallcacocha 1 | Rodbell et al. (1999) | −4.77 | −79.23 |
| B | N-Andes | 2143 | Papallacta PA 1-08 | Ledru et al. (2013) | −0.36 | −78.19 |
| B | N-Andes | 1181 | Tres Lagunas | Jantz and Behling (2012) | −3.03 | −79.23 |
| B | N-Andes | 1160 | Laguna Zurita | Niemann and Behling (2010) | −3.03 | −79.23 |
| B | N-Andes | 1749 | ECSF Refugio | Niemann and Behling (2010) | −3.99 | −79.07 |
| B | N-Andes | 1144 | El Junco EJ1 | Colinvaux and Schofield (1976) | −0.50 | −91.00 |
| C | C-Andes | 2518 | Cerro Llamoca | Schittek et al. (2015) | −14.17 | −74.73 |
| C | C-Andes | 1520 | Marcacocha | Chepstow-Lusty et al. (1998, 2003, 2009) | −11.39 | −76.12 |
| C | C-Andes | 1496 | Chica-Soras | Branch et al. (2007) | −14.18 | −73.53 |
| C | C-Andes | 1516 | Pacucha | Hillyer et al. (2009), Valencia et al. (2010) | −13.61 | −73.50 |
| C | C-Andes | 1514 | Consuelo | Urrego et al. (2010) | −13.95 | −69.00 |
| C | C-Andes | 1555 | Urpi Cocha Lagoon Core 2 | Winsborough et al. (2012) | −12.23 | −76.88 |
| C | C-Andes | 1546 | Nevado Coropuna | Kuentz et al. (2012) | −15.50 | −72.67 |
| D | Amazon | 1211 | Quistococha | Roucoux et al. (2013) | −3.83 | −73.32 |
| D | Amazon | 1558 | Werth | Bush et al. (2007a, b) | −12.18 | −69.10 |
| D | Amazon | 2991 | Laguna Granja | Carson et al. (2014) | −13.26 | −63.71 |
| D | Amazon | 0460 | Fazenda Cigana | Da Silva Menenses et al. (2013) | −3.45 | −61.30 |
| D | Amazon | 3004 | French Guiana K-VIII | Iriarte et al. (2012) | 5.20 | −52.69 |
| D | Amazon | 1498 | Gentry | Bush et al. (2007a, b) | −12.33 | −68.87 |
| D | Amazon | 1549 | Parker | Bush et al. (2007a, b) | −12.18 | −69.10 |
| D | Amazon | 0518 | Lake Geral C | Bush et al. (2000, 2007b) | −1.65 | −53.60 |





CPD
11, 3475–3565, 2015

**Table 3.** Continued.

| Fig. 6 | Region | LAPD ID | Site Name | Potentially suitable for 2 k climate modelling | Potentially suitable for human studies | LOTRED-2 k | DUR 500 | CONTROL2 | TOP_END | 1000_MID3 |
|---|---|---|---|---|---|---|---|---|---|---|
| D | Amazon | 0599 | Terra Indigena Aningal | 1 | 1 | 3 | 1 | 1 | 1 | 0 |
| D | Amazon | 1557 | Vargas | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| D | Amazon | 2993 | Laguna El Cerrito | 0 | 1 | 3 | 1 | 1 | 0 | 1 |
| D | Amazon | 2994 | Laguna Frontera | 0 | 1 | 3 | 1 | 1 | 0 | 1 |
| D | Amazon | 2995 | Laguna San José | 0 | 1 | 3 | 1 | 1 | 0 | 1 |
| D | Amazon | 0339 | Laguna Chaplin | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| D | Amazon | 0566 | Rio Curua | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| D | Amazon | 0521 | Lake Tapera | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| D | Amazon | 0483 | Lago Crispim | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| D | Amazon | 1166 | Maxus-1 | 1 | 0 | 3 | 1 | 1 | 0 | 1 |
| E | SE Brazil | 0582 | Sao Josú dos Ausentes | 0 | 1 | 4 | 1 | 1 | 1 | 1 |
| E | SE Brazil | 3005 | Morro Santana | 0 | 1 | 4 | 1 | 1 | 1 | 1 |
| E | SE Brazil | 1998 | Rincâo das Cabritas | 1 | 1 | 3 | 1 | 1 | 1 | 0 |
| E | SE Brazil | 0437 | Cambará do Sul | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| E | SE Brazil | 0591 | Serra dos Orgâos | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| E | SE Brazil | 0479 | Lagao Nova | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| E | SE Brazil | 1962 | Ciama 2 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| E | SE Brazil | 0487 | Lago do Pires | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| E | SE Brazil | 0579 | Saõ Francisco de Assis | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| F | Pampa | 2998 | Hinojales-San Leoncio | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| F | Pampa | 2423 | Lake Lonkoy | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| F | Pampa | 0216 | Laguna Sauce Grance | 1 | 0 | 3 | 1 | 1 | 1 | 0 |
| G | S-And./Patag | 0745 | Onamonte | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0050 | Puerto Harberton | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0242 | Valle de Andorra | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 1990 | Cabo Virgenes | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| G | S-And./Patag | 2996 | Cabo Virgenes CV22 | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| G | S-And./Patag | 0083 | Lago Azul | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0792 | Rio Rubens | 0 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0102 | Lago Potrok Aike | 0 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0734 | Lago Cipreses | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0050 | Lago Guanaco | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0025 | Cerro Frias | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| G | S-And./Patag | 3000 | Peninsula Avellanedo Bajo | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 2484 | Parque Nacional Perito Moreno | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0657 | Mallin Pollux | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 1964 | Mallin El Embudo | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 1965 | Lago Shaman | 1 | 1 | 3 | 1 | 0 | 1 | 1 |
| G | S-And./Patag | 0099 | Lago Mosquito | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 2501 | Lago Lepué | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 2321 | Lago Pichilafquen | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 2320 | Lago San Pedro | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0661 | Lago Aculeo | 1 | 1 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 0749 | Palo Colorado | 1 | 0 | 4 | 1 | 1 | 1 | 1 |
| G | S-And./Patag | 2996 | Abra del Infernillo | 1 | 0 | 4 | 1 | 1 | 1 | 1 |





CPD
11, 3475–3565, 2015

## **Table 3.** Continued.

| Fig. 6 | Region | LAPD ID | Site Name | Human Indicators | First human indicator (cal yr BP) | Precip. Sensitive | Temp. Sensitive |
|---|---|---|---|---|---|---|---|
| D | Amazon | 0599 | Terra Indigena Aningal | Charcoal, forest decrease, savanna increase | > 2000? | X | |
| D | Amazon | 1557 | Vargas | Charcoal | 1000 | X | |
| D | Amazon | 2993 | Laguna El Cerrito | *Z. mays*/charcoal | 2000 | | |
| D | Amazon | 2994 | Laguna Frontera | *Z. mays*/charcoal | 2000 | | |
| D | Amazon | 2995 | Laguna San José | *Z. mays*/charcoal | ca. 1600 | | |
| D | Amazon | 0339 | Laguna Chaplin | *Z. mays* (unpubl.) | ca. 1300 | | |
| D | Amazon | 0566 | Rio Curua | Charcoal, forest decrease | ca. 2500 | X | |
| D | Amazon | 0521 | Lake Tapera | Charcoal | ca. 6900 | X | |
| D | Amazon | 0483 | Lago Crispim | Charcoal, mangrove decrease | > 2000 | | |
| D | Amazon | 1166 | Maxus-1 | No | | X | |
| E | SE Brazil | 0582 | Sao Josú dos Ausentes | Grasses, charcoal, *Pinus* | 500 | | |
| E | SE Brazil | 3005 | Morro Santana | Charcoal, *Z. mays*, *Pinus*, *Eucalyptus* | 1230 | | |
| E | SE Brazil | 1998 | Rincâo das Cabritas | Grasses, fire increase (since early and mid-Holocene) | 30 | X | X |
| E | SE Brazil | 0437 | Cambará do Sul | Charcoal, grasses | 170 | X | X |
| E | SE Brazil | 0591 | Serra dos Orgâos | Charcoal (?) | | X | X |
| E | SE Brazil | 0479 | Lagao Nova | Charcoal? | Early and mid-Holocene? | X | |
| E | SE Brazil | 1962 | Ciama 2 | Grasses, *Pinus* | 160 | X | X |
| E | SE Brazil | 0487 | Lago do Pires | Deforestation, *Z. mays*, charcoal (since early and mid-Holocene) | 140 | X | |
| E | SE Brazil | 0579 | Saõ Francisco de Assis | Charcoal (begin Holocene), *Z. mays* (1.9 ka) | 10000 | X | |
| F | Pampa | 2998 | Hinojales-San Leoncio | Exotic tree species (*Eucalyptus*, *Pinus*) | 100 | X | |
| F | Pampa | 2423 | Lake Lonkoy | Exotic tree species (*Eucalyptus*, *Pinus*) | 100 | X | |
| F | Pampa | 0216 | Laguna Sauce Grance | No | | | |
| G | S-And./Patag | 0745 | Onamonte | No | | X | |
| G | S-And./Patag | 0050 | Puerto Harberton | No | | X | |
| G | S-And./Patag | 0242 | Valle de Andorra | No | | | |
| G | S-And./Patag | 1990 | Cabo Virgenes | *Rumex* presence | 50 | X | |
| G | S-And./Patag | 2996 | Cabo Virgenes CV22 | *Rumex* presence | 50 | X | |
| G | S-And./Patag | 0083 | Lago Azul | *Rumex* presence | 50 | X | |
| G | S-And./Patag | 0792 | Rio Rubens | *Rumex* presence | 300 | X | |
| G | S-And./Patag | 0102 | Lago Potrok Aike | Chenopodiaceae increase, *Rumex* presence | 150 | X | |
| G | S-And./Patag | 0734 | Lago Cipreses | *Rumex* presence, increase of shrub and herbs taxa | 60 | X | |
| G | S-And./Patag | 0050 | Lago Guanaco | *Rumex*, increase of Poaceae and *Plantago* | 60 | X | |
| G | S-And./Patag | 0025 | Cerro Frias | *Nothofagus* decrease, *Rumex* presence | 155 | X | |
| G | S-And./Patag | 3000 | Peninsula Avellanedo Bajo | Exotic species presence (Ast. Asteroideae, *Rumex*) | 25 | X | |
| G | S-And./Patag | 2484 | Parque Nacional Perito Moreno | No | | | X |
| G | S-And./Patag | 0657 | Mallin Pollux | Increase of Poaceae, *Pinus* and *Plantago* | 100 | X | |
| G | S-And./Patag | 1964 | Mallin El Embudo | Increase of Poaceae | 100 | X | |
| G | S-And./Patag | 1965 | Lago Shaman | Asteraceae sub Asteroidea | 250 | X | |
| G | S-And./Patag | 0099 | Lago Mosquito | *Nothofagus* decrease, *Rumex* and *Pinus* presence | 200 | X | |
| G | S-And./Patag | 2501 | Lago Lepué | No | | X | |
| G | S-And./Patag | 2321 | Lago Pichilafquen | *Rumex*, *Pinus* presence | 350 | X | X |
| G | S-And./Patag | 2320 | Lago San Pedro | *Rumex*, *Pinus*, *Plantago* presence, Poaceae increase | 121 | X | X |
| G | S-And./Patag | 0661 | Lago Aculeo | Micoralgae, Chenopodiaceae increase | 100 | X | |
| G | S-And./Patag | 0749 | Palo Colorado | Decrease of swamp forest taxa, increase of *Maytenus* and Asteraceae | < 620 | X | |
| G | S-And./Patag | 2996 | Abra del Infernillo | No | | X | |

**Table 3.** Continued.

| Fig. 6 | Region | LAPD ID | Site Name | References | Latitude (decimal degrees) | Longitude (decimal degrees) |
|---|---|---|---|---|---|---|
| D | Amazon | 0599 | Terra Indigena Aningal | Da Silva Menenses et al. (2013) | −3.45 | −61.3 |
| D | Amazon | 1557 | Vargas | Bush et al. (2007a, b) | −12.33 | −69.12 |
| D | Amazon | 2993 | Laguna El Cerrito | Whitney et al. (2014) | −13.25 | −65.39 |
| D | Amazon | 2994 | Laguna Frontera | Whitney et al. (2014) | −13.22 | −65.35 |
| D | Amazon | 2995 | Laguna San José | Whitney et al. (2013) | −14.95 | −64.50 |
| D | Amazon | 0339 | Laguna Chaplin | Mayle et al. (2000), Burbridge et al. (2004) | −14.48 | −61.06 |
| D | Amazon | 0566 | Rio Curua | Behling and Da Costa (2000) | −1.74 | −51.46 |
| D | Amazon | 0521 | Lake Tapera | Toledo and Bush (2007) | 0.13 | −51.08 |
| D | Amazon | 0483 | Lago Crispim | Behling and Da Costa (2001) | −0.77 | −47.85 |
| D | Amazon | 1166 | Maxus-1 | Weng et al. (2002) | −0.45 | −76.62 |
| E | SE Brazil | 0582 | Sao Josú dos Ausentes | Jeske-Pieruschka et al. (2010) | −28.94 | −50.04 |
| E | SE Brazil | 3005 | Morro Santana | Behling et al. (2007) | −30.08 | −51.10 |
| E | SE Brazil | 1998 | Rincâo das Cabritas | Jeske-Pieruschka and Behling (2012) | −29.48 | −50.57 |
| E | SE Brazil | 0437 | Cambará do Sul | Behling et al. (2004) | −29.05 | −50.10 |
| E | SE Brazil | 0591 | Serra dos Orgâos | Behling and Safford (2010) | −22.46 | −43.03 |
| E | SE Brazil | 0479 | Lagao Nova | Behling (2003) | −17.97 | −42.20 |
| E | SE Brazil | 1962 | Ciama 2 | Jeske-Pieruschka et al. (2013) | −27.90 | −48.87 |
| E | SE Brazil | 0487 | Lago do Pires | Behling (1995) | −17.95 | −42.22 |
| E | SE Brazil | 0579 | Saõ Francisco de Assis | Behling et al. (2005) | −29.59 | −55.22 |
| F | Pampa | 2998 | Hinojales-San Leoncio | Stutz et al. (2015) | −37.57 | −57.45 |
| F | Pampa | 2423 | Lake Lonkoy | Stutz et al. (2012, 2015) | −37.20 | −57.42 |
| F | Pampa | 0216 | Laguna Sauce Grance | Fontana (2005) | −38.95 | −61.37 |
| G | S-And./Patag | 0745 | Onamonte | Heusser (1993) | −54.90 | −68.95 |
| G | S-And./Patag | 0050 | Puerto Harberton | Markgraf and Huber (2007) | −54.88 | −67.17 |
| G | S-And./Patag | 0242 | Valle de Andorra | Mauquoy et al. (2004) | −54.75 | −68.30 |
| G | S-And./Patag | 1990 | Cabo Virgenes | Mancini (2007) | −52.33 | −68.38 |
| G | S-And./Patag | 2996 | Cabo Virgenes CV22 | Mancini and Graham (2014) | −52.33 | −68.40 |
| G | S-And./Patag | 0083 | Lago Azul | Mayr et al. (2005) | −52.08 | −69.58 |
| G | S-And./Patag | 0792 | Rio Rubens | Huber and Markgraf (2003) | −52.07 | −71.93 |
| G | S-And./Patag | 0102 | Lago Potrok Aike | Wille et al. (2007), Schäbitz et al. (2013) | −51.97 | −70.38 |
| G | S-And./Patag | 0734 | Lago Cipreses | Moreno et al. (2014) | −51.29 | −72.85 |
| G | S-And./Patag | 0050 | Lago Guanaco | Moreno et al. (2009) | −51.05 | −73.38 |
| G | S-And./Patag | 0025 | Cerro Frias | Tonello et al. (2009), Mancini (2009) | −50.40 | −72.70 |
| G | S-And./Patag | 3000 | Peninsula Avellanedo Bajo | Echeverria et al. (2014) | −50.27 | −72.84 |
| G | S-And./Patag | 2484 | Parque Nacional Perito Moreno | Mancini et al. (2002) | −47.88 | −72.85 |
| G | S-And./Patag | 0657 | Mallin Pollux | Markgraf et al. (2007) | −45.69 | −71.84 |
| G | S-And./Patag | 1964 | Mallin El Embudo | de Porras et al. (2014) | −44.67 | −71.70 |
| G | S-And./Patag | 1965 | Lago Shaman | de Porras et al. (2012) | −44.45 | −71.09 |
| G | S-And./Patag | 0099 | Lago Mosquito | Whitlock et al. (2006) | −42.83 | −71.67 |
| G | S-And./Patag | 2501 | Lago Lepué | Pesce and Moreno (2014) | −42.80 | −73.33 |
| G | S-And./Patag | 2321 | Lago Pichilafquen | Jara and Moreno (2012, 2014) | −41.14 | −72.80 |
| G | S-And./Patag | 2320 | Lago San Pedro | Fletcher and Moreno (2012) | −38.53 | −71.32 |
| G | S-And./Patag | 0661 | Lago Aculeo | Villa-Martínez et al. (2004) | −33.83 | −70.90 |
| G | S-And./Patag | 0749 | Palo Colorado | Maldonado and Villagrán (2006) | −32.08 | −71.48 |
| G | S-And./Patag | 2996 | Abra del Infernillo | Garralla (2003) | −26.75 | −66.75 |



CPD
11, 3475–3565, 2015

**Table 4.** Abbreviations.

| | |
|---|---|
| 2 k | last 2000 calibrated years (short writing for: 2000 cal yr BP) |
| ALLJ | Andean Low-Level Jet |
| AMO | Atlantic Multidecadal Oscillation |
| BP | Before Present, present defined as AD 1950 |
| C | Central |
| cal kyr | thousand calibrated years before present |
| Cheno/Am | Chenopodiaceae/Amaranthaceae |
| DJF | December–January–February |
| ENSO | El Niño–Southern Oscillation |
| GS | Gran Sabana |
| IPO | Interdecadal Pacific Oscillation |
| ITCZ | Inter-Tropical Convergence Zone |
| JJA | June–July–August |
| ka | thousand calibrated years before present, cal kyr BP |
| LAPD | Latin American Pollen Database |
| LIA | Little Ice Age |
| LOTRED-SA | LOng-Term multi-proxy climate REconstructions and Dynamics in South America |
| m a.s.l. | meters above sea level |
| MCA | Medieval Climate Anomaly |
| NE | northeast(ern) |
| NW | northwest(ern) |
| P/E | Precipitation/Evapotranspiration ratio |
| S | south(ern) |
| SA | South America |
| SACZ | South Atlantic Convergence Zone |
| SAM | Southern Annular Mode |
| SASM | South American Summer Monsoon |
| SE | southeast(ern) |
| SPA | Subtropical Pacific Anticyclone |
| SST | Sea Surface Temperature |
| SWWB | Southern Westerly Wind Belt |
| TNA | Tropical North Atlantic SST |
| TSA | Tropical South Atlantic SST |
| UFL | upper forest line |
| W | west(ern) |





CPD
11, 3475–3565, 2015

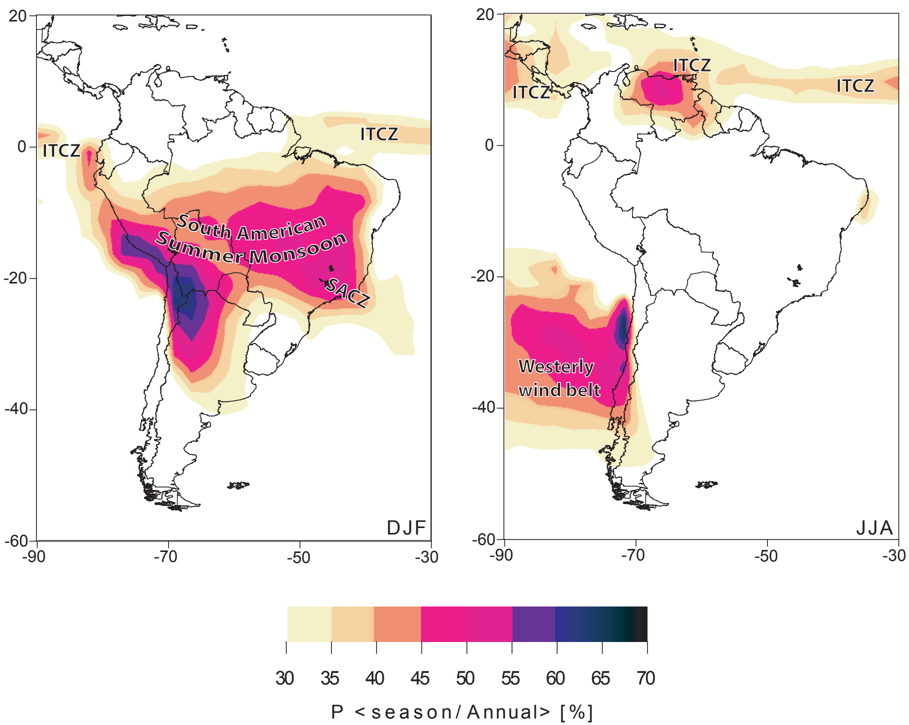


**Figure 1.** Map showing the relative precipitation amount over South America during the key seasons DJF (austral summer and mature monsoon phase) and JJA (dry season over much of tropical South America), highlighting the Intertropical Convergence Zone (ITCZ), South American Summer Monsoon (SASM), South Atlantic Convergence Zone (SACZ) and extratropical westerlies. Figure based on CMAP precipitation data. Adapted after Vuille et al. (2012).



CPD
11, 3475–3565, 2015

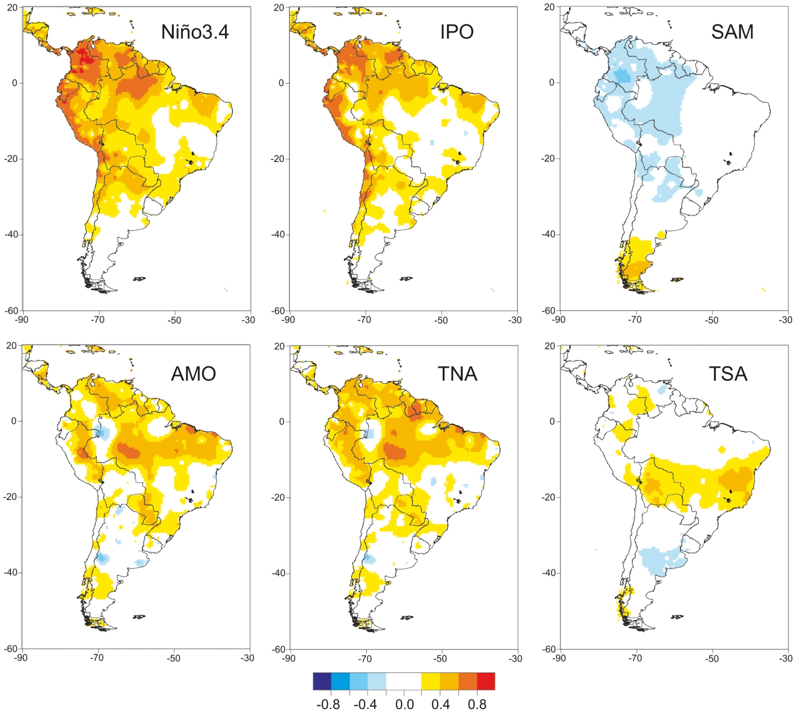


**Figure 2.** Correlation of annual mean temperature over South America with climate modes Niño3.4, IPO (Interdecadal Pacific Oscillation), SAM (Southern Annular Mode), AMO (Atlantic Multidecadal Oscillation), TNA (Tropical North Atlantic SST) and TSA (Tropical South Atlantic SST). High positive values of the correlation coefficient indicate both increasing/decreasing values of the mode in question and the local temperature at each grid cell. High negative values indicate that the increasing (/decreasing) mode in question cause a significant decrease (/increase) in temperature at the grid cell. Gridded temperature fields are from University of Delaware (1958–2008). Only correlations in excess of ±0.2 are shown (roughly the threshold of the 95 % significance level).





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

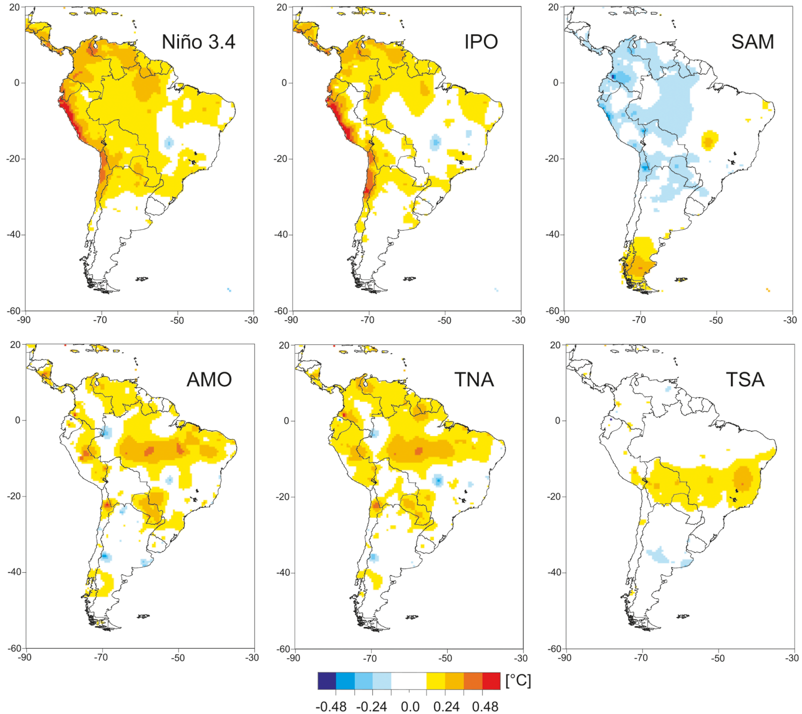


**Figure 3.** Annual mean temperature regressed upon regression with modes Niño3.4, IPO (Interdecadal Pacific Oscillation), SAM (Southern Annular Mode), AMO (Atlantic Multidecadal Oscillation), TNA (Tropical North Atlantic SST), TSA (Tropical South Atlantic SST). High positive values of the regression coefficient indicate high anomalies during the mode in question and the local temperature at each grid cell. High negative values indicate that the increasing mode in question cause a significant decrease in temperature at the grid cell. Gridded temperature fields are from University of Delaware (1958–2008).





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

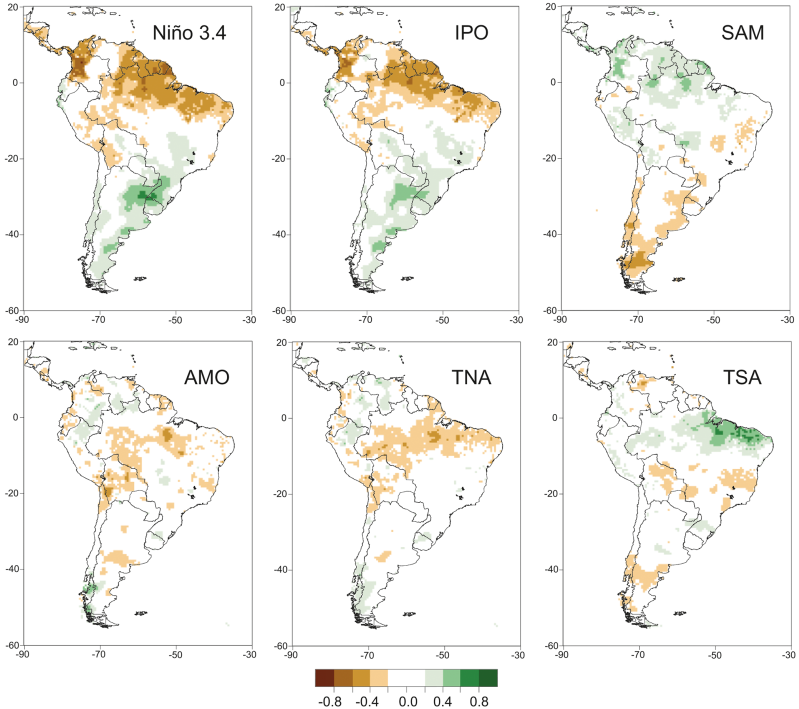


**Figure 4.** Precipitation correlation with modes Niño3.4, IPO (Interdecadal Pacific Oscillation), SAM (Southern Annular Mode), AMO (Atlantic Multidecadal Oscillation), TNA (Tropical North Atlantic SST), TSA (Tropical South Atlantic SST). High positive values of the correlation coefficient indicate both increasing/decreasing values of the mode in question and the local precipitation at each grid cell. High negative values indicate that the increasing (/decreasing) mode in question cause a significant decrease (/increase) in precipitation at the grid cell.





CPD
11, 3475–3565, 2015

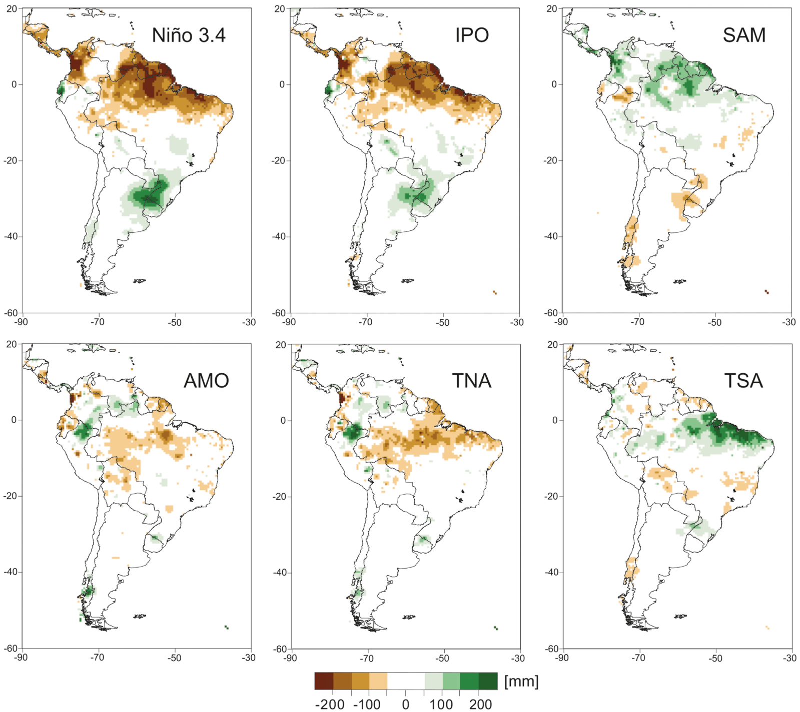


**Figure 5.** Precipitation regression with modes Niño3.4, IPO (Interdecadal Pacific Oscillation), SAM (Southern Annular Mode), AMO (Atlantic Multidecadal Oscillation), TNA (Tropical North Atlantic SST), TSA (Tropical South Atlantic SST). High positive values of the regression coefficient indicate high anomalies during the mode in question and the local precipitation at each grid cell. High negative values indicate that the increasing mode in question cause a significant decrease in precipitation at the grid cell.





CPD
11, 3475–3565, 2015

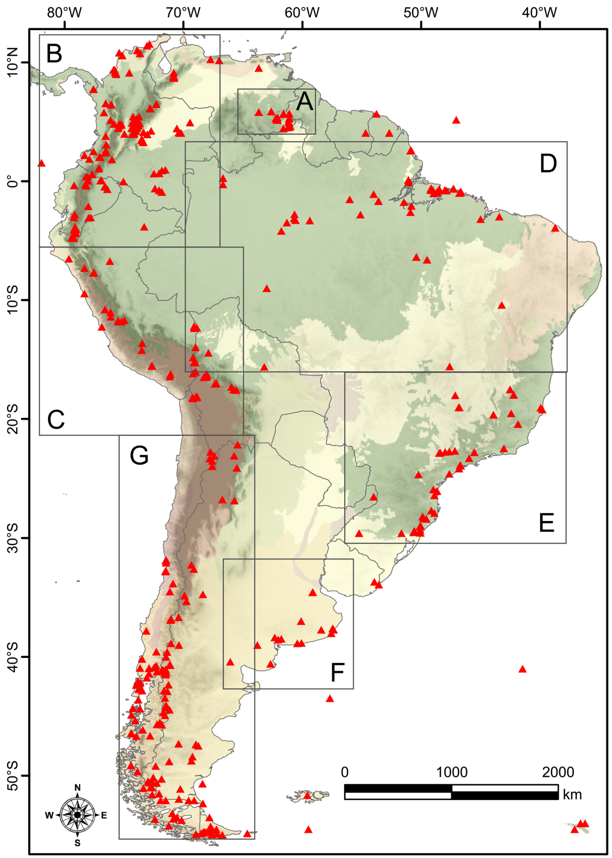


**Figure 6.** Map showing the location of LAPD pollen records that cover the last 2 ka (after Flantua et al., 2015a). General regional delimitations as discussed in this paper are shown; A: Venezuelan Guyana highlands and uplands; B: Northern Andes; C: Central Andes; D: Lowland Amazon basin; E: Southern and southeastern Brazil.; F: Pampa plains; G: Southern Andes and Patagonia.





CPD
11, 3475–3565, 2015

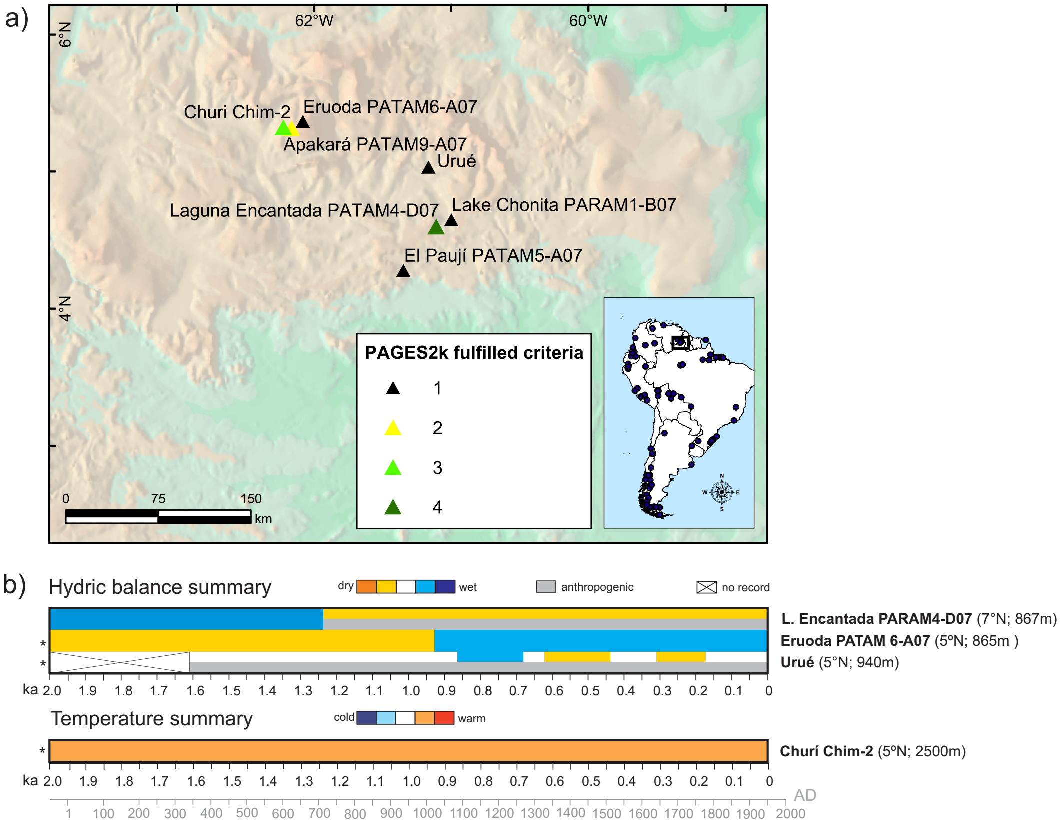


**Figure 7. (a)** Map showing the discussed pollen records in the Venezuelan Guayana highlands and uplands. **(b)** Summary of hydric balance and temperature including human interference for the pollen records discussed. * Records fulfilling 1 or 2 criteria.





CPD
11, 3475–3565, 2015

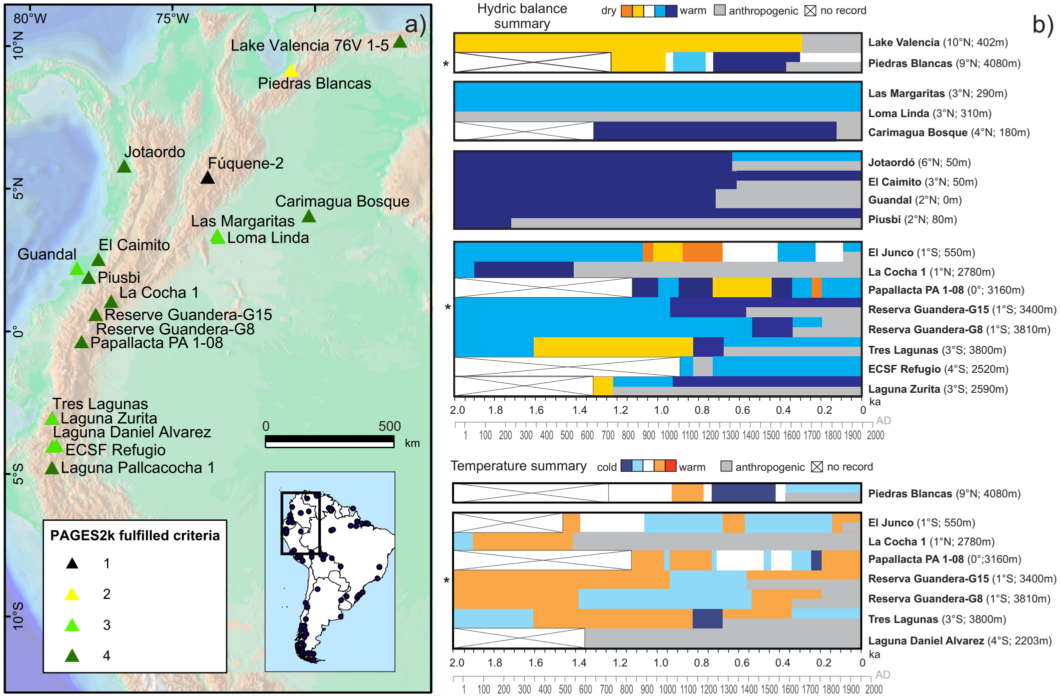


**Figure 8. (a)** Map showing the discussed pollen records in the Northern Andes. **(b)** Summary of hydric balance and temperature including human interference for the pollen records discussed. * Records fulfilling 1 or 2 criteria (m±: m a.s.l. based on coordinates).



CPD

11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

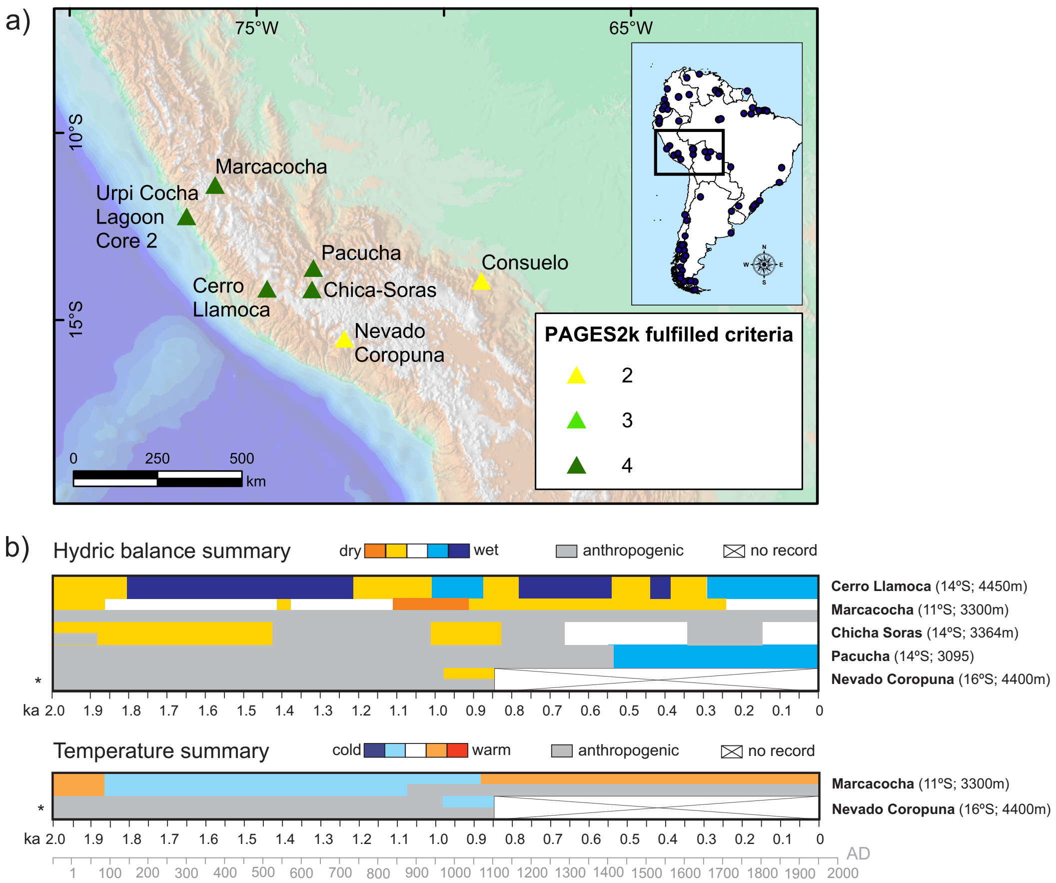


**Figure 9. (a)** Map showing the discussed pollen records in the central Andes. **(b)** Summary of hydric balance and temperature including human interference for the pollen records discussed. * Records fulfilling 1 or 2 criteria.



CPD

11, 3475–3565, 2015

**Climate variability and human impact in South America during the last 2000 years**

S. G. A. Flantua et al.

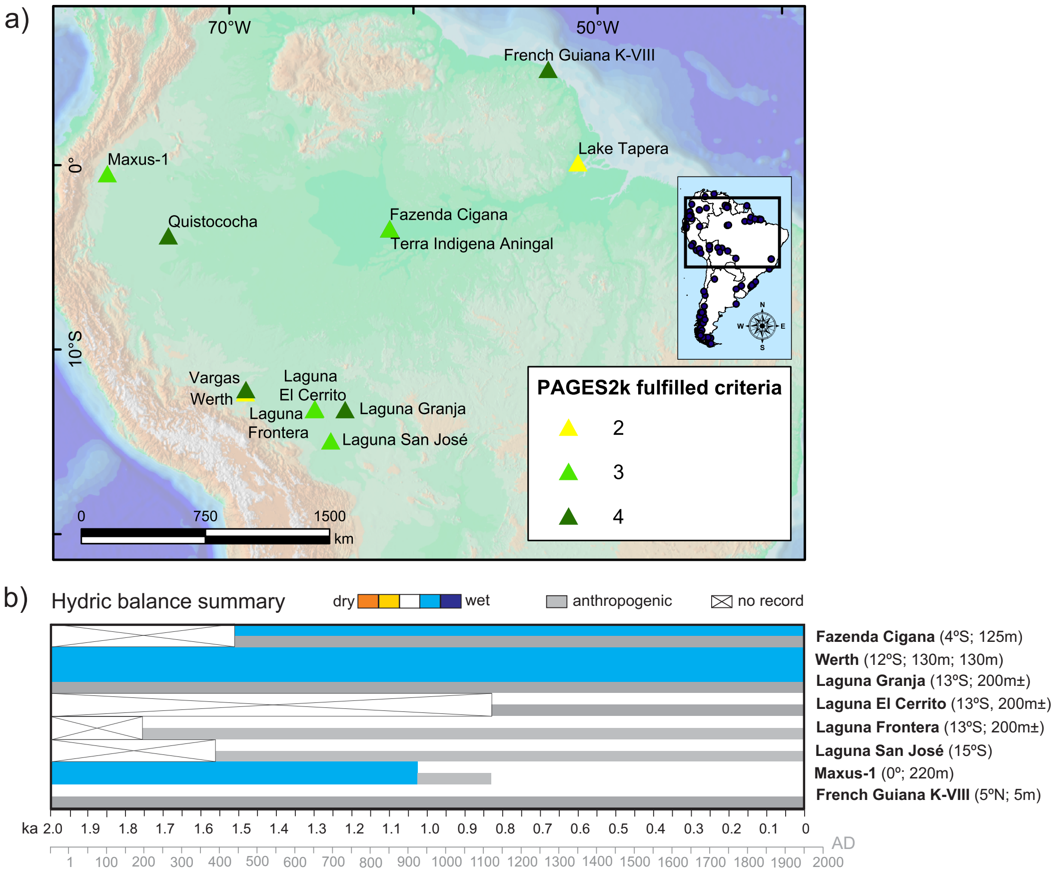


**Figure 10. (a)** Map showing the discussed pollen records in the Lowland Amazon Basin. **(b)** Summary of hydric balance including human interference for the pollen records discussed (temperature summary could not be inferred) (m±: m a.s.l. based on coordinates).





CPD
11, 3475–3565, 2015

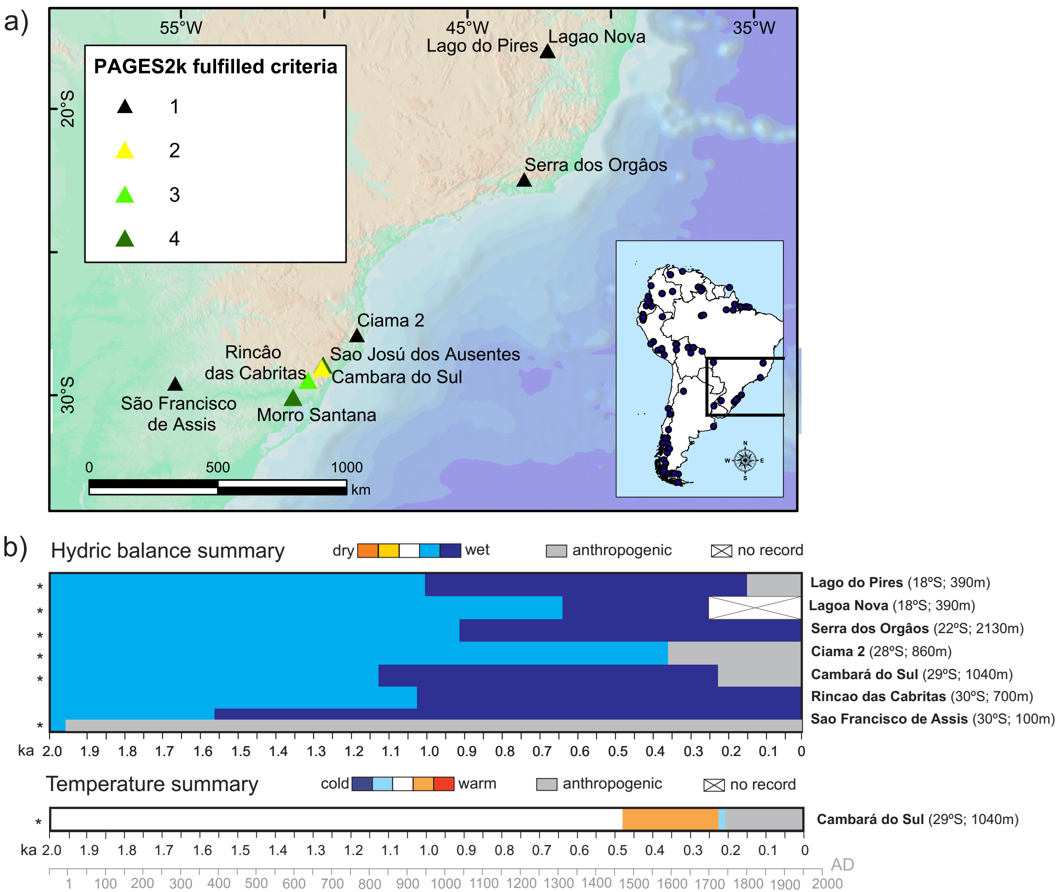


**Figure 11. (a)** Map showing the discussed pollen records in the Southern and Southeastern Brazil. **(b)** Summary of hydric balance and temperature including human interference for the pollen records discussed. * Records fulfilling 1 or 2 criteria.





CPD
11, 3475–3565, 2015

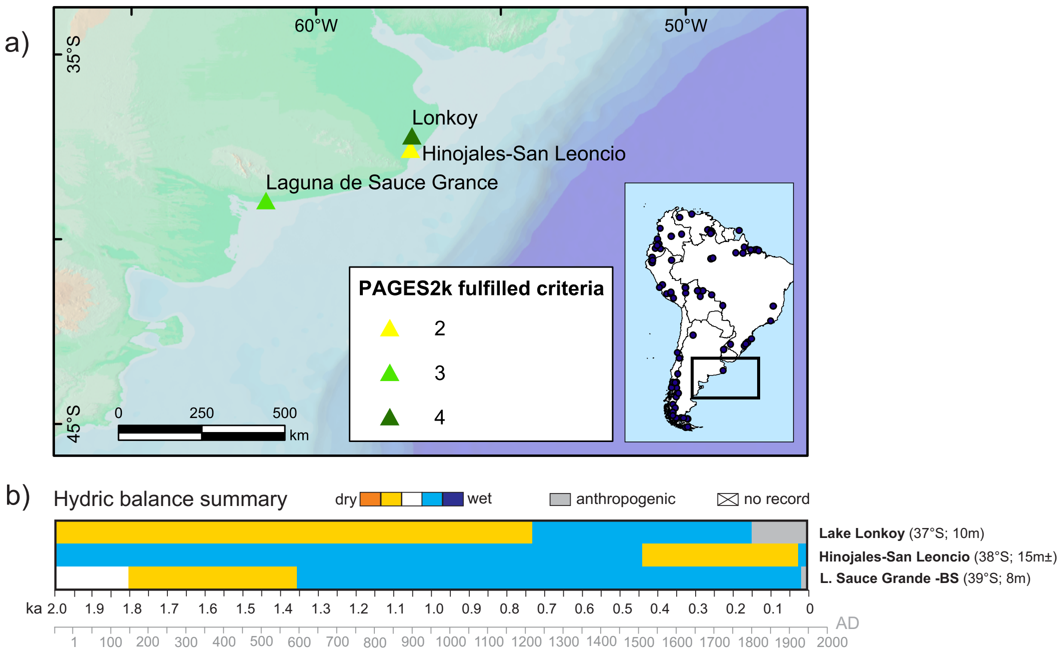


**Figure 12. (a)** Map showing the discussed pollen records in the Pampa plains. **(b)** Summary of hydric balance including human interference for the pollen records discussed (temperature summary could not be inferred) (m±: m a.s.l. based on coordinates).





CPD
11, 3475–3565, 2015

CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.



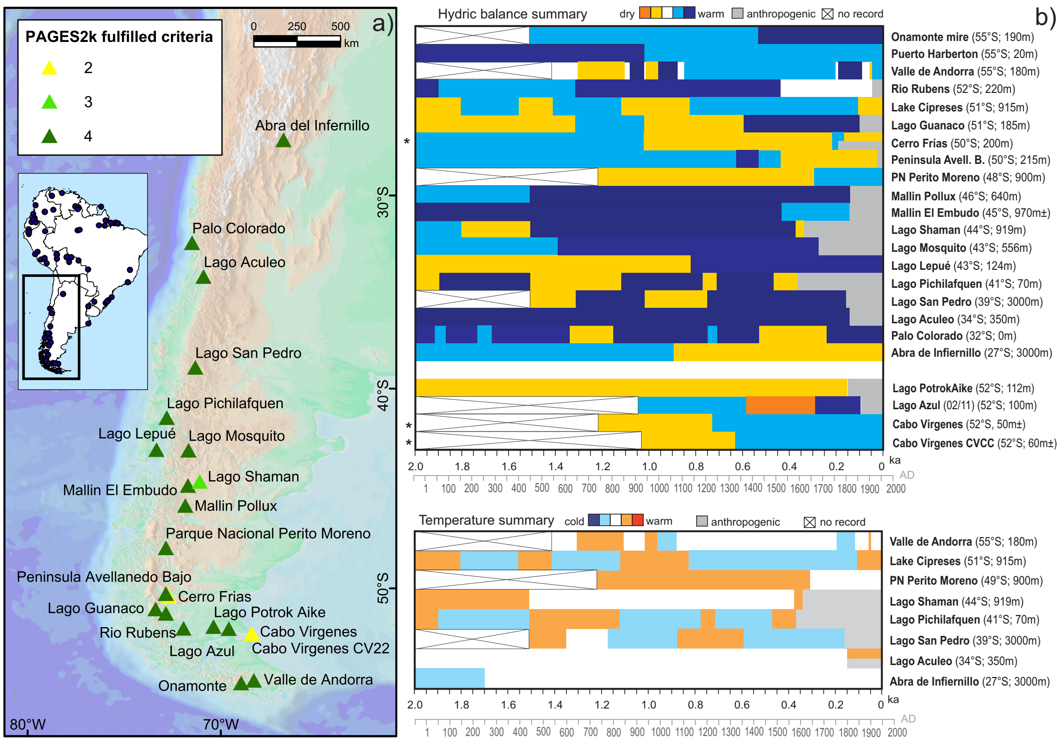


**Figure 13. (a)** Map showing the discussed pollen records in the Southern Andes and Patagonia. **(b)** Summary of hydric balance and temperature including human interference for the pollen records discussed. * Records fulfilling 1 or 2 criteria (m±: m a.s.l. based on coordinates).

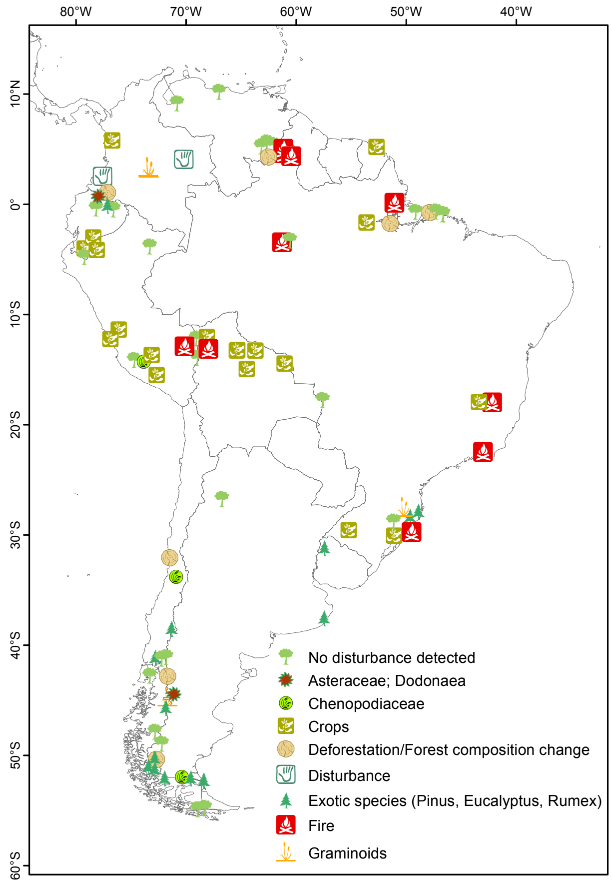


**Figure 14.** Map showing human indicators observed in the discussed pollen records. Additional details are found in Table 3.





CPD
11, 3475–3565, 2015

Climate variability and human impact in South America during the last 2000 years

S. G. A. Flantua et al.